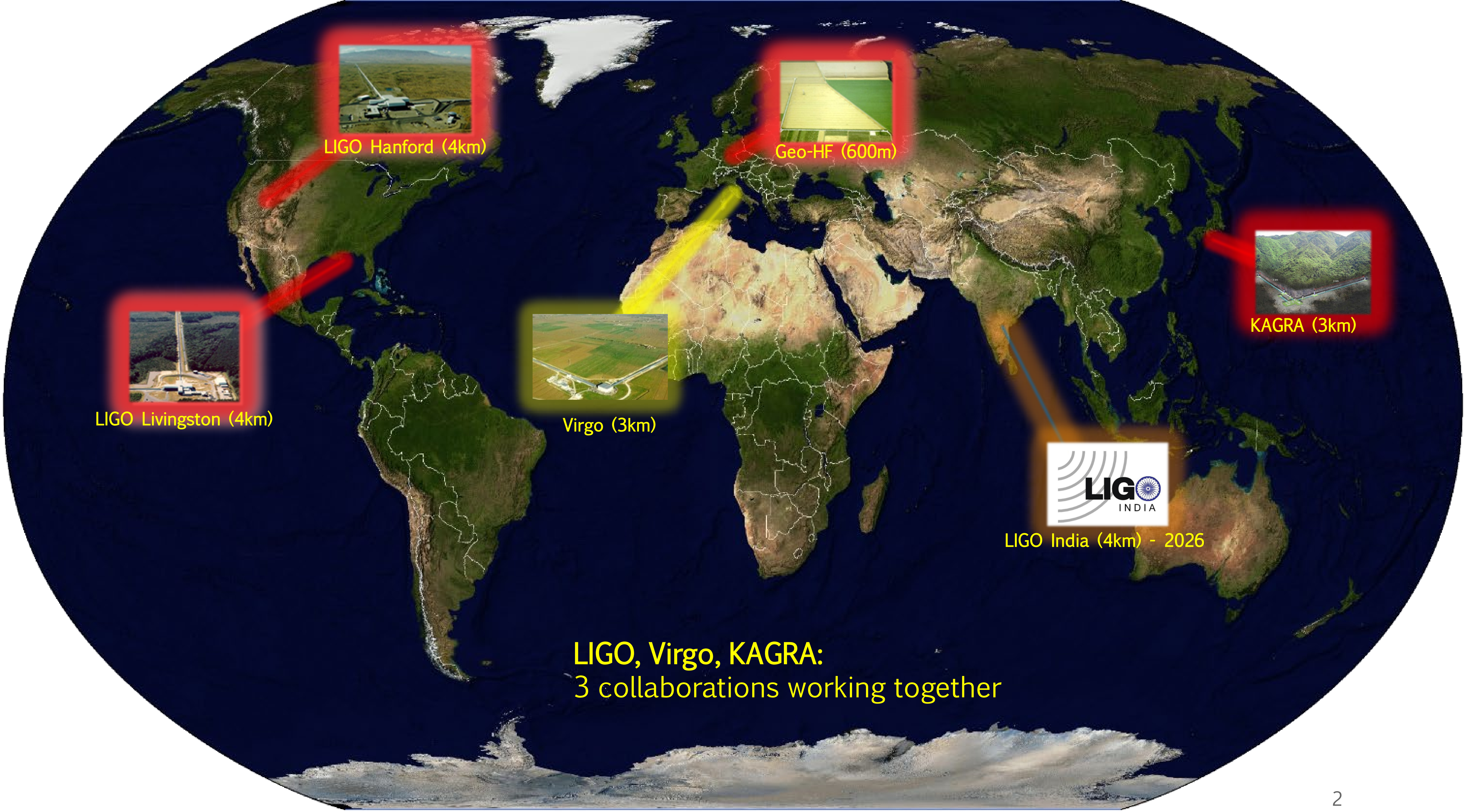
VIRGO DATA ANALYSIS & MUILTI-MESSENGER ASPECTS

Giancarlo Cella – VIRGO COLLABORATION/INFN PISA



LIGO, Virgo, KAGRA:

3 collaborations working together

DA Organization

- ☐ All data analysis activities of interest to Virgo-LIGO-KAGRA are a joint business of both collaborations

Joint LIGO Virgo KAGRA working groups

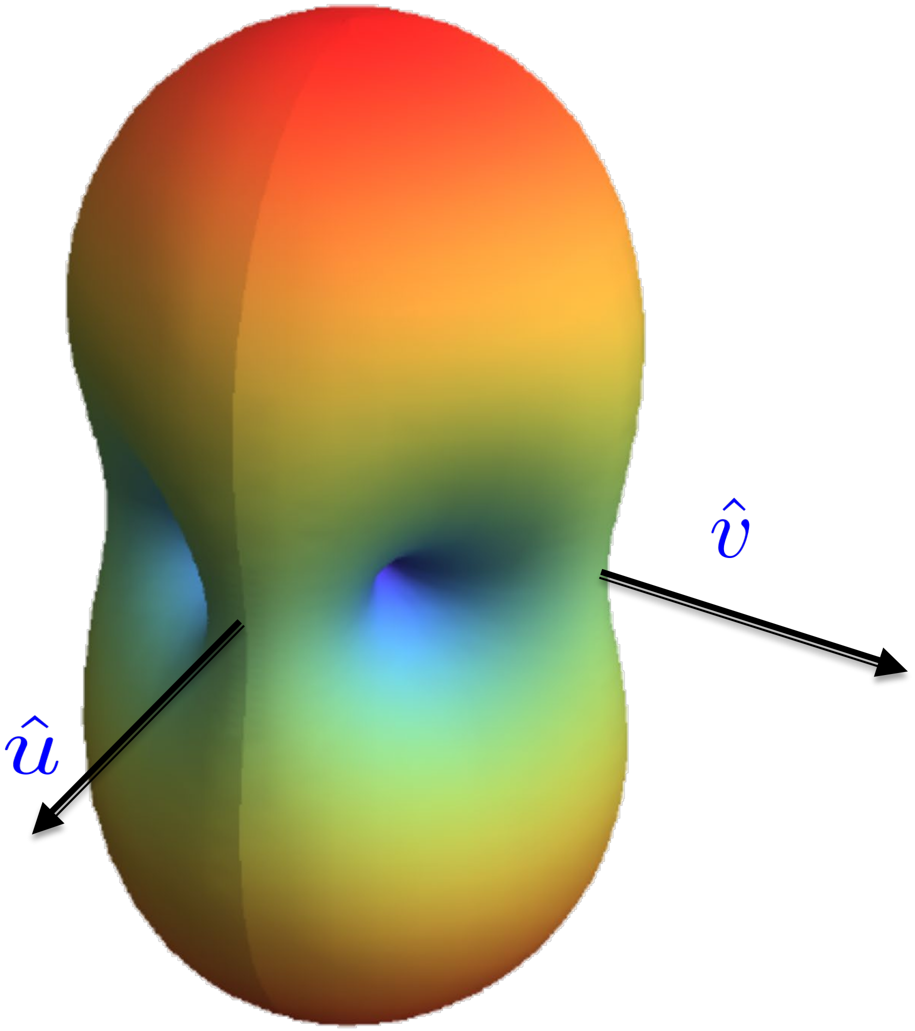
- ☐ LIGO-Virgo-KAGRA data analysis activities for GWs are planned on the basis of the joint **data analysis white paper**, released yearly
- ☐ Tight coupling with:
  - ☐ Detector characterization
  - ☐ Computing and software
  - ☐ Calibration
  - ☐ Low latency working group

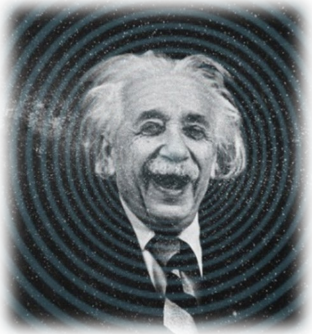
Detector tensor and angular sensitivity pattern

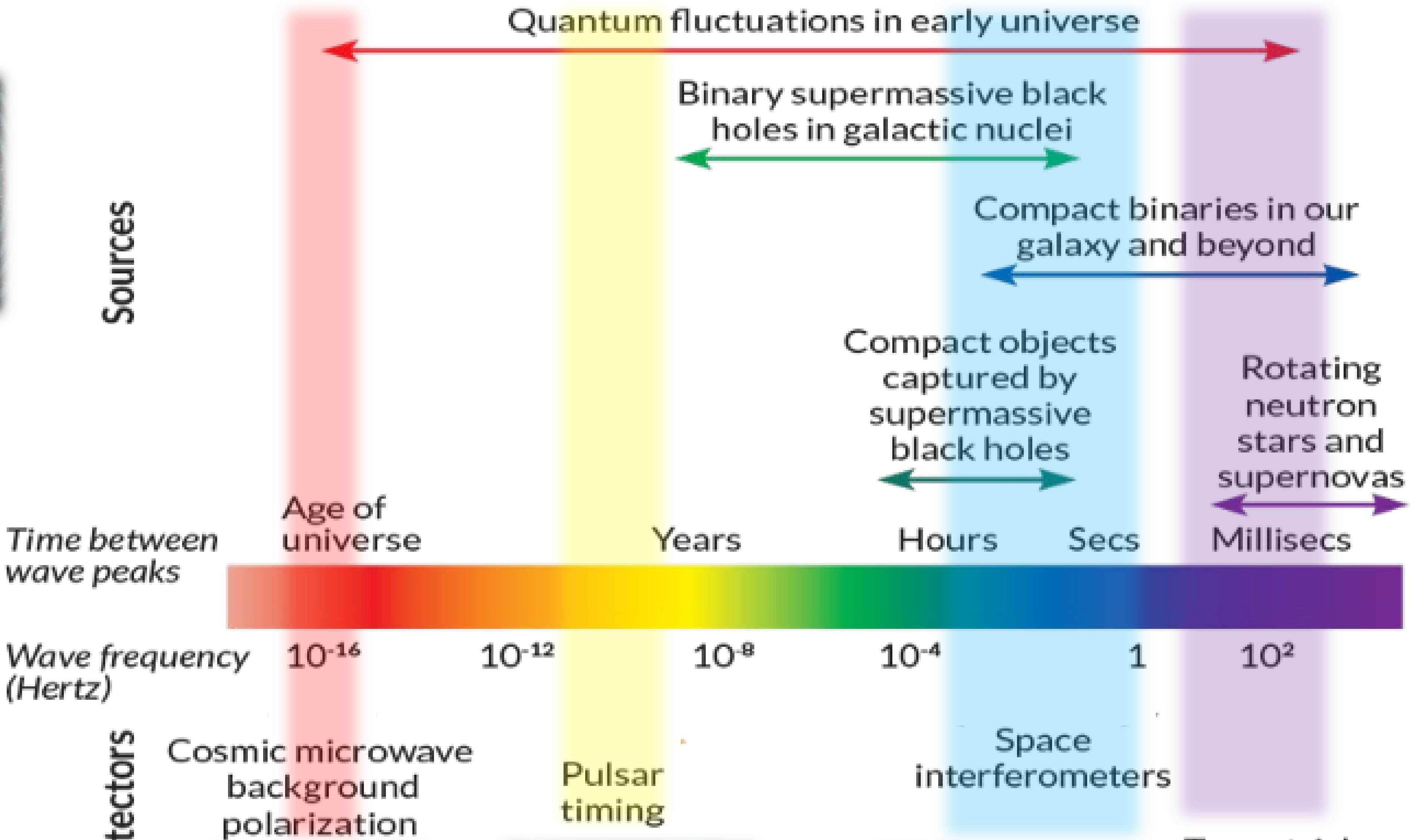
- We can represent as a function of the GW's direction of propagation

$$\Gamma(\hat{n}) = D^{ij}\left[\cos\psi\,\epsilon^{+}_{ij}(\hat{n}) + \sin\psi\,\epsilon^{\times}_{ij}(\hat{n})\right]$$

- For each $\hat{n}$ there is an optimal polarization angle ψ_{opt}
- $\psi_{opt} + \pi/2$ gives a decoupled polarization
- This gives the directionality of an interferometric detector







Sources

Quantum fluctuations in early universe

Binary supermassive black holes in galactic nuclei

Compact binaries in our galaxy and beyond

Compact objects captured by supermassive black holes

Rotating neutron stars and supernovas

Time between wave peaks

Age of universe

Years

Hours

Secs

Millisecs

Wave frequency (Hertz)

10^{-16}

10^{-12}

10^{-8}

10^{-4}

1

10^{2}

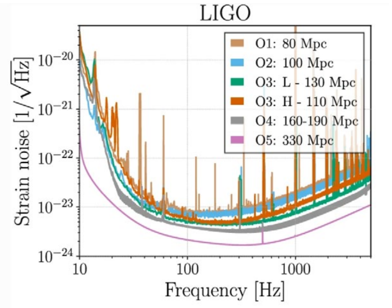
Detectors

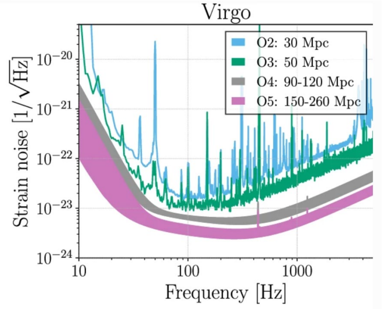
Cosmic microwave background polarization

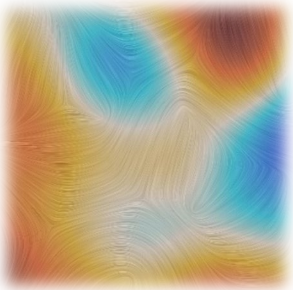
Pulsar timing

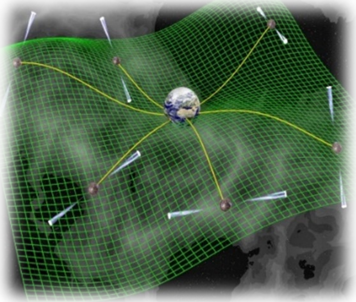
Space interferometers

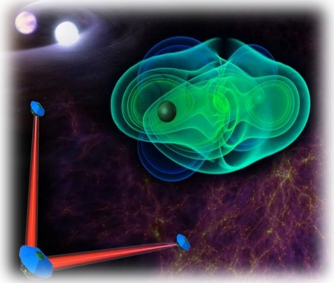
Terrestrial interferometers











Living Rev Relativ **23,** 3 (2020).
https://doi.org/10.1007/s41114-020-00026-9

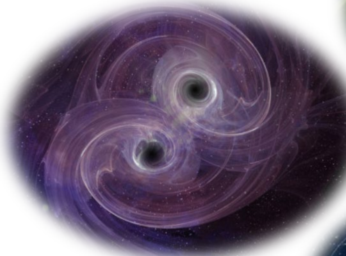
Gravitational wave observations

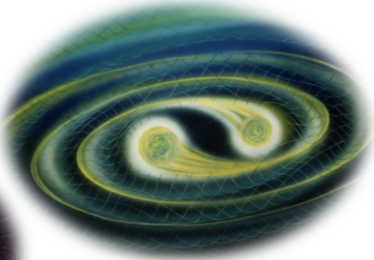
Several kind of searches, roughly classified in 4 groups:

- ☐ **Burst:** search for transients with minimal assumptions about signal's shape

Core collapse massive stars, cosmic strings, …

- ☐ **CBC:** *signals from compact binary coalescences, searched with specific, theoretically motivated (GR or alternative models) waveforms.*



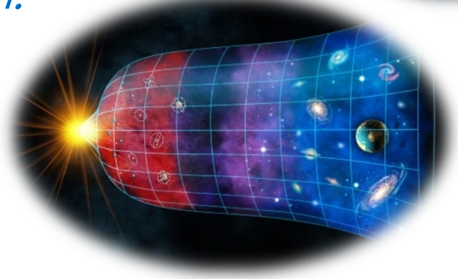


Coalescing binaries:
✓ BH-BH,
✓ NS-NS,
✓ BH-NS

- ☐ **CW:** *continuous signals: rotating neutron stars, …..*

Spinning NS (Isolated or not), Instabilities, …

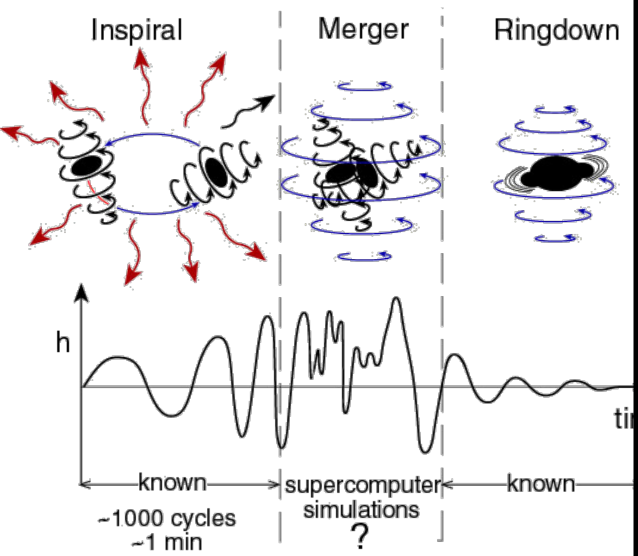
- ☐ **Stochastic:** *stochastic signals, astrophysical or cosmological origin.*

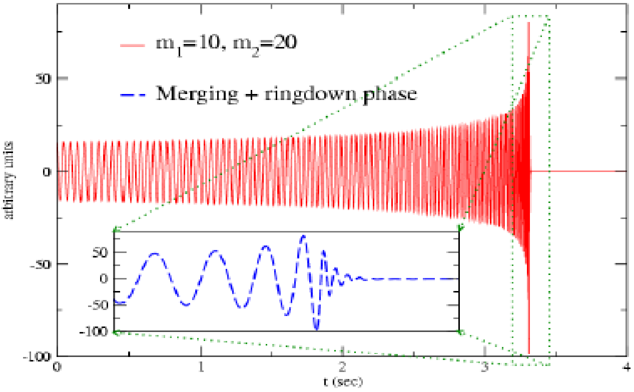


Inflation, phase transitions, cosmic strings, astrophysical backgrounds,…

Direct information about mass-energy distribution, unique or complementary observative channel.

Coalescing binaries



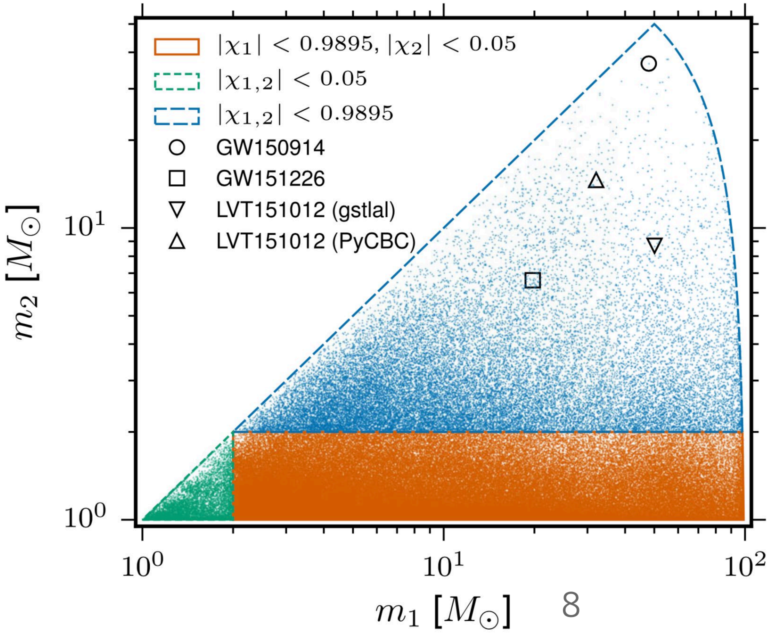


A first tool: the Wiener filter

$$W\left(\vec{\alpha}, s\right] = \int_0^\infty \frac{\tilde{T}(\vec{\alpha}, f)^*\, \tilde{s}(f)}{S(f)} df$$

- A scalar product between observed and theoretical signal
- Weighted with the noise power spectrum
- Detection comparison between $\max_{\alpha} W$ and a threshold
- About 250000 templates
- Parameter estimation
  - fast (low latency);
  - One for each detector;

Accurate parameter estimation uses a different approach



A second tool: the Bayes’ theorem

- If we know the statistical properties of detector’s noise we can write

$$P\left(\underbrace{s_1,\cdots,s_N}_{\text{Data (known)}}|\vec{\alpha}\right)$$

Parameters (unknown)

- From Bayes’ theorem it follows

$$P\left(\vec{\alpha}|s_1,\cdots,s_N\right)=\frac{P\left(s_1,\cdots,s_N|\,\vec{\alpha}\right)P\left(\vec{\alpha}\right)}{P\left(s_1,\cdots,s_N\right)}$$

- This is the «mother of all information»
- Takeaway message: waveform can contain detailed information about parameters
- We will see some example in the following…..

Other analysis methods, in a nutshell

- **Continuous waves**
  - Basically, known signal (but with interesting exceptions)
  - But the optimal Wiener filter approach is too much demanding
  - Suboptimal approaches: compromise between computational power and coherence/sensitivity
- **Bursts**
  - Unknown signals
  - Several variant of energy excess test, taking advantage of minimal assumptions, such as
    - Very short signal
    - Consistency between different detectors
- **Stochastic background**
  - "Signal" can be modeled only in a statistical way, as a random process
  - Stationary
  - Gaussian (but this is not necessarily true)

$$\langle s^H s^L \rangle = \langle h^H h^L \rangle + \cancel{\langle h^H n^L \rangle} + \cancel{\langle n^H h^L \rangle} + \cancel{\langle n^H n^L \rangle}$$

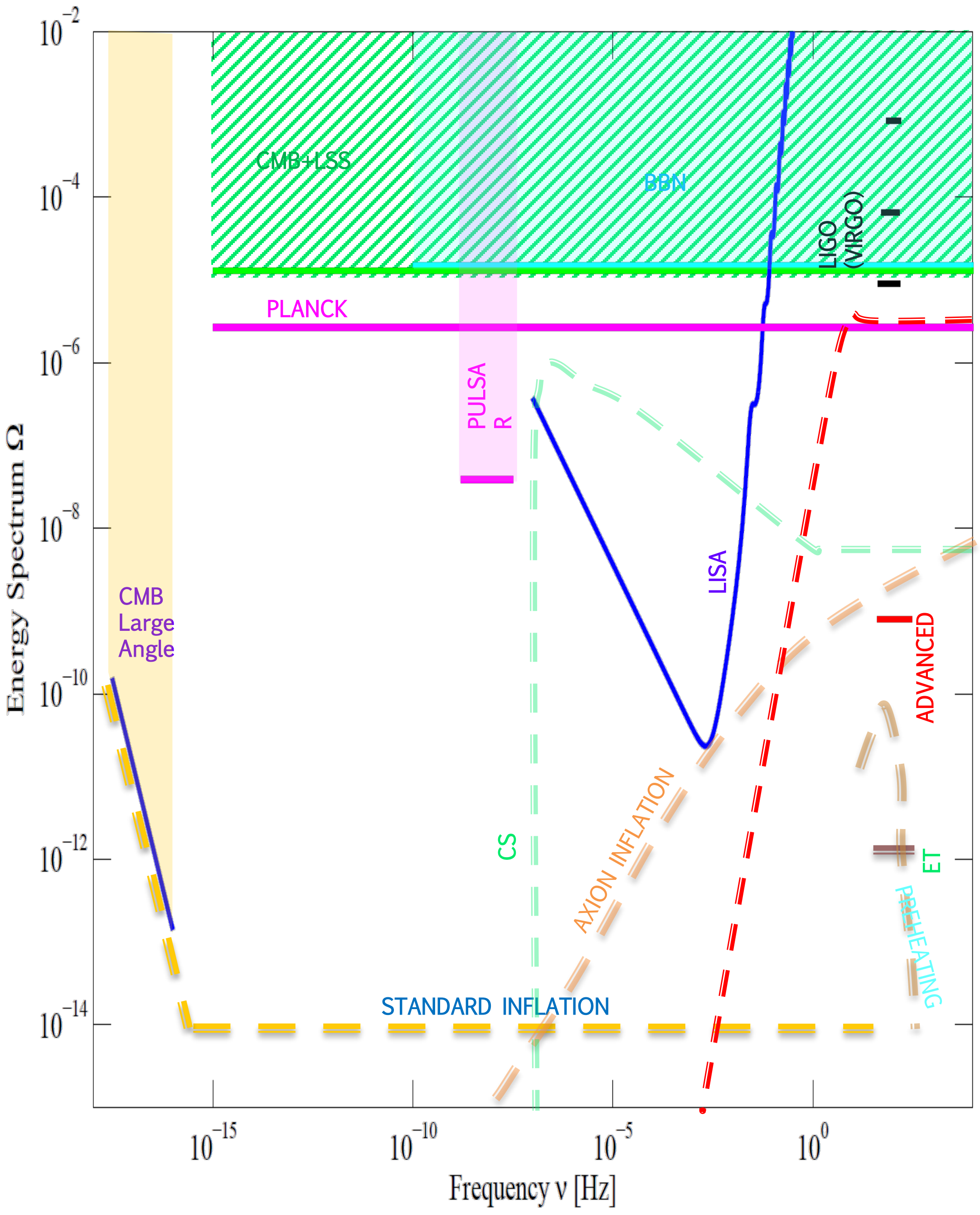
- If we assume isotropy, all the information is contained in the signal power spectrum

$$S(f) = \frac{3H_0^2}{10\pi^2}\frac{\Omega_{GW}(f)}{f^3}$$

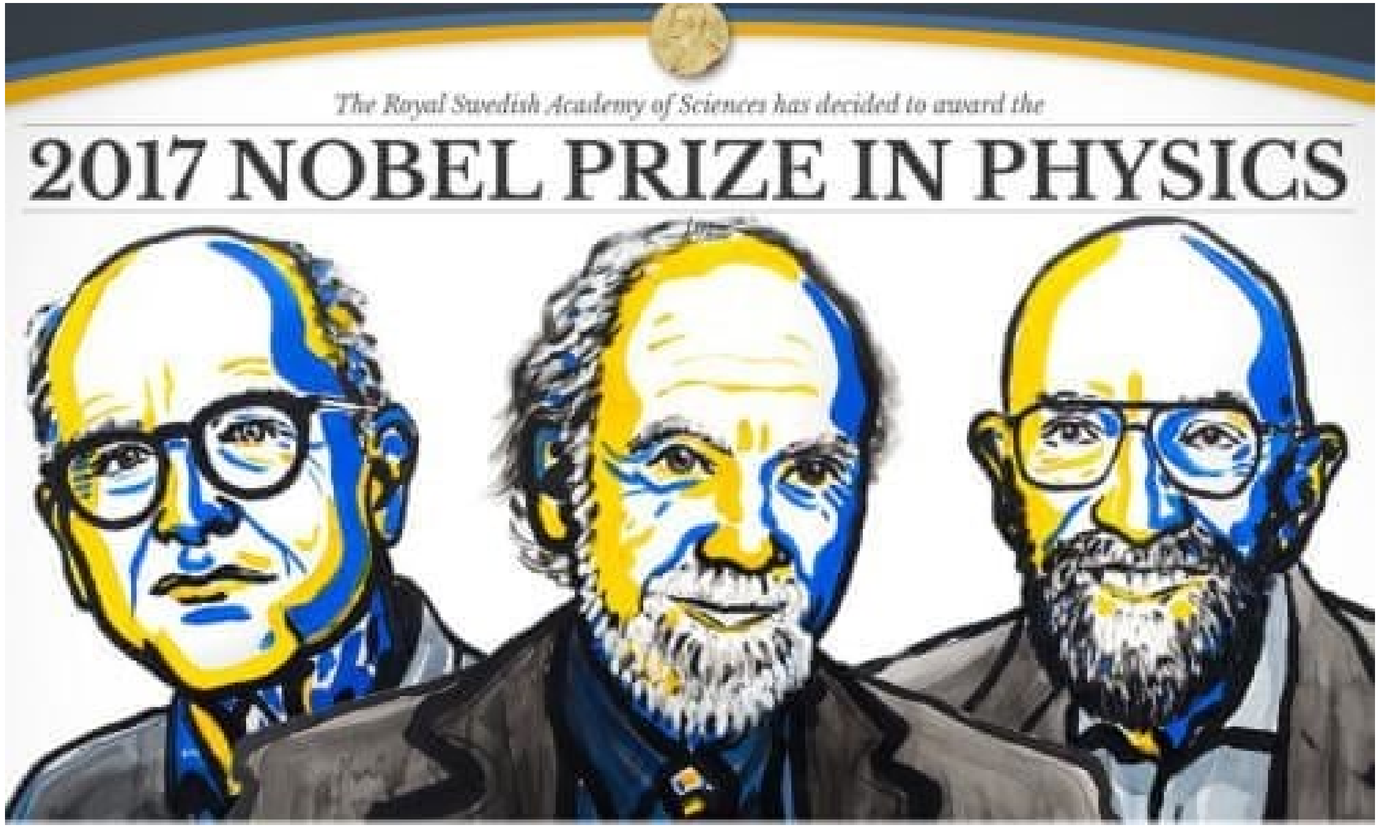
which can be directly estimated. But we can do more.....

Cosmological SB

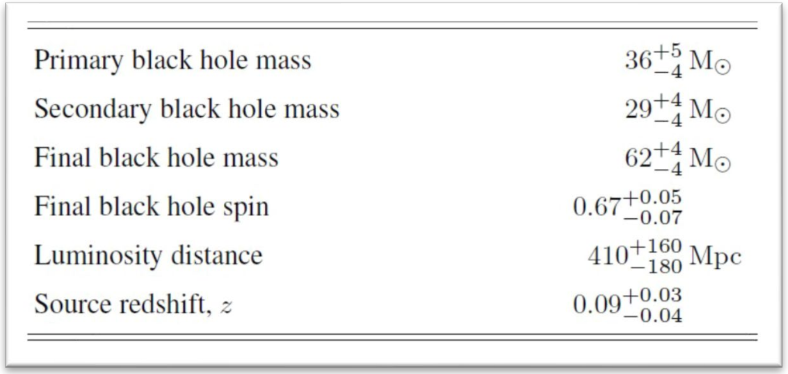
- Several possible backgrounds:
  - Inflation models
  - Cosmic strings
  - Phase transitions
- We started to have a high enough sensitivity to improve BBN-CMB upper bound
- Some models accessible with advanced detectors



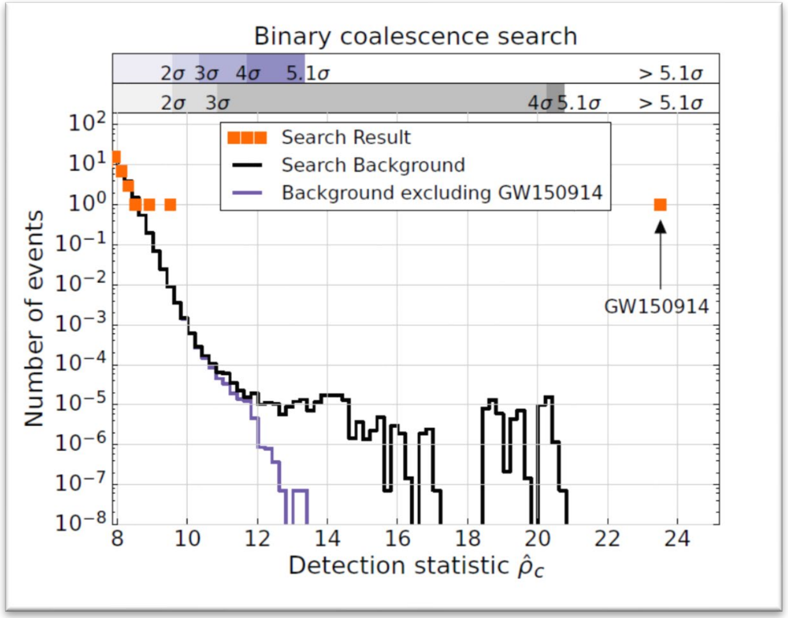
THE FIRST 5 YEARS OF OBSERVATIONS



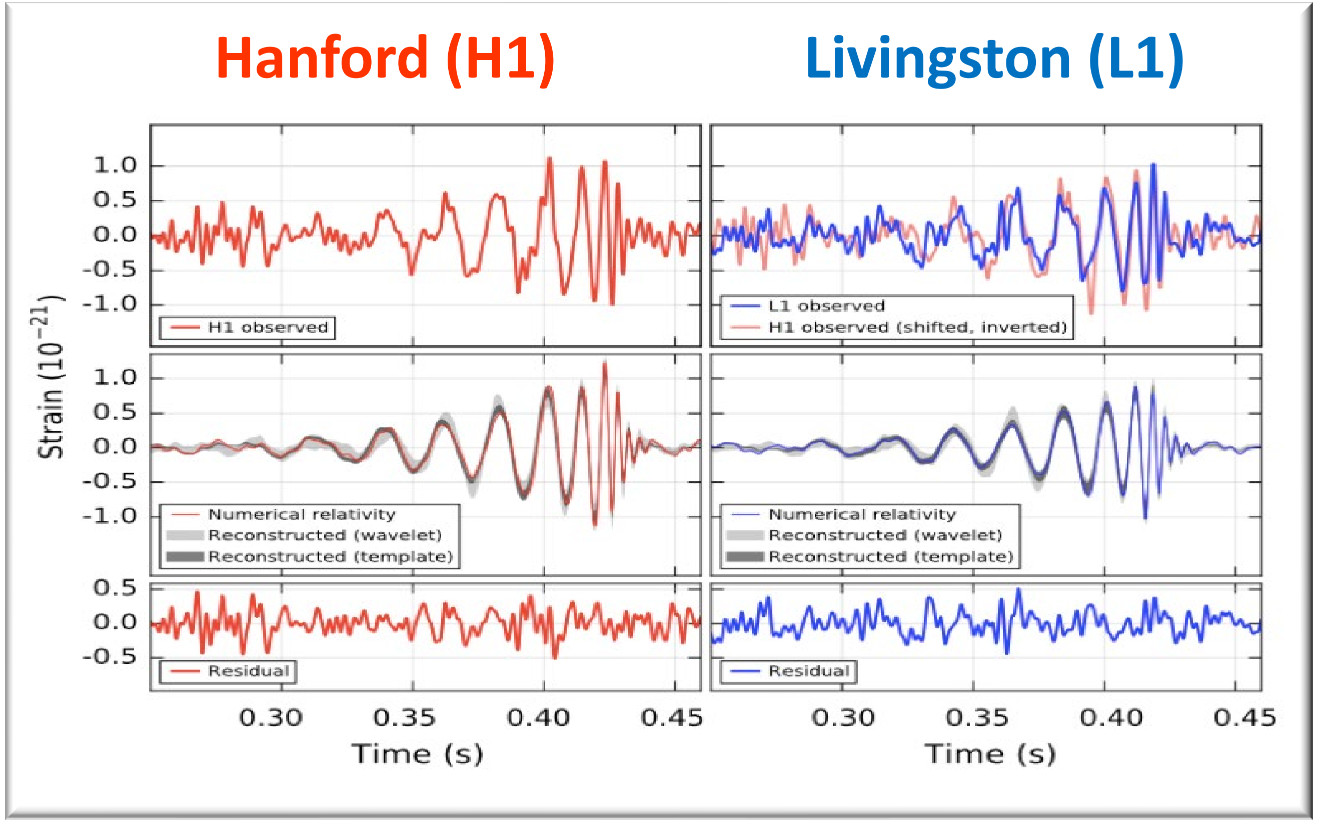
GW150914: the first direct GW observation



Primary black hole mass	$36^{+5}_{-4}\,\mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,\mathrm{M}_\odot$
Final black hole mass	$62^{+4}_{-4}\,\mathrm{M}_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	$410^{+160}_{-180}\,\mathrm{Mpc}$
Source redshift, z	$0.09^{+0.03}_{-0.04}$

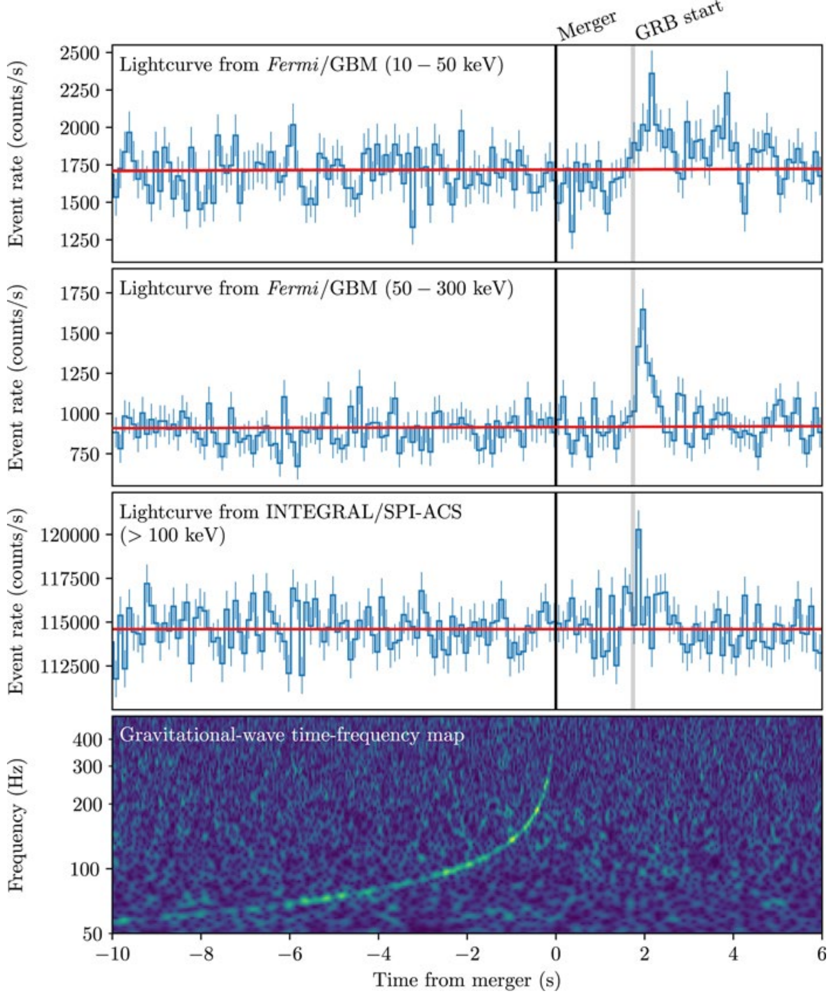


- P_{FA} = 1/203000 yr^{-1}
- Significativity > 5.3σ



Interpretation: BBH coalescence
Similar events followed:

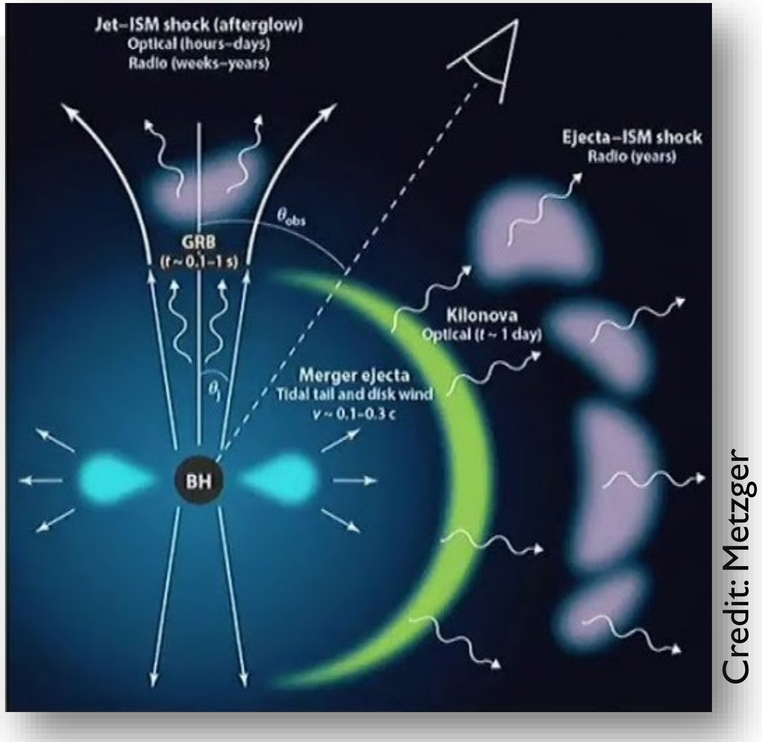
- **GW150914** (September 14th 2015)
- **GW151226** (December 26th 2015)
- **GW170104** (January 4th 2016)



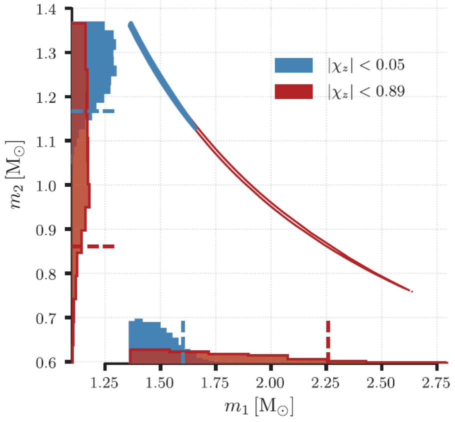
[Phys. Rev. Lett. 119, 161101 (2017)](#) [Astrophys. J. Lett. 848, L12 (2017)](#) [Astrophys. J. Lett. 848, L13 (2017)](#)

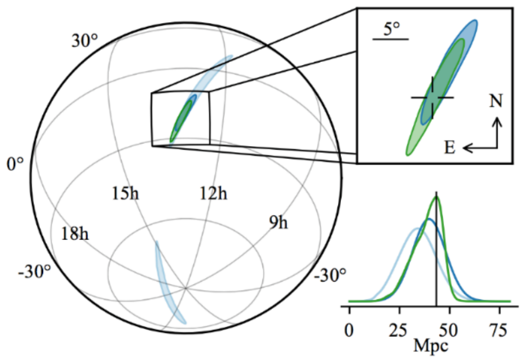
GW170817: a BNS coalescence

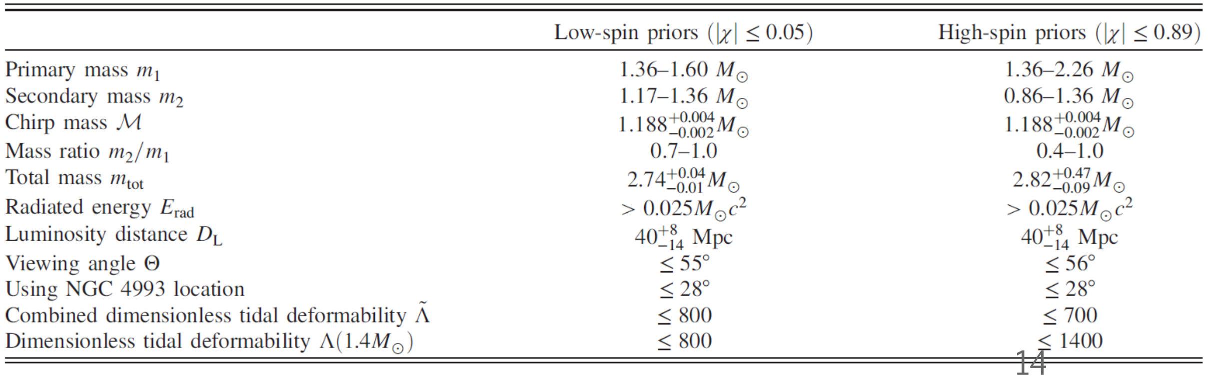
- Seen in GW data
- Cohincident (in 2s) with a short GRB detected by Fermi/GBM & INTEGRAL (not so energetic, probably off axis)
- Well localized (31 deg^2 ➔ 16 deg^2)
- Optical counterpart found in host galaxy NGC 4993
- Kilonova
- Afterglow observations



Credit: Metzger

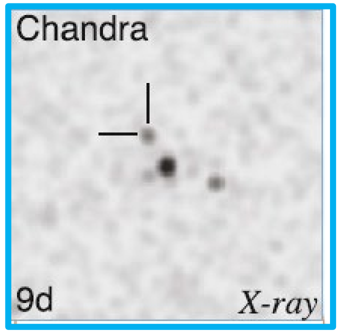


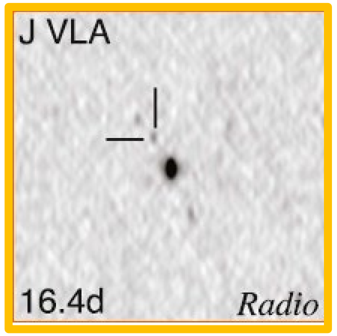




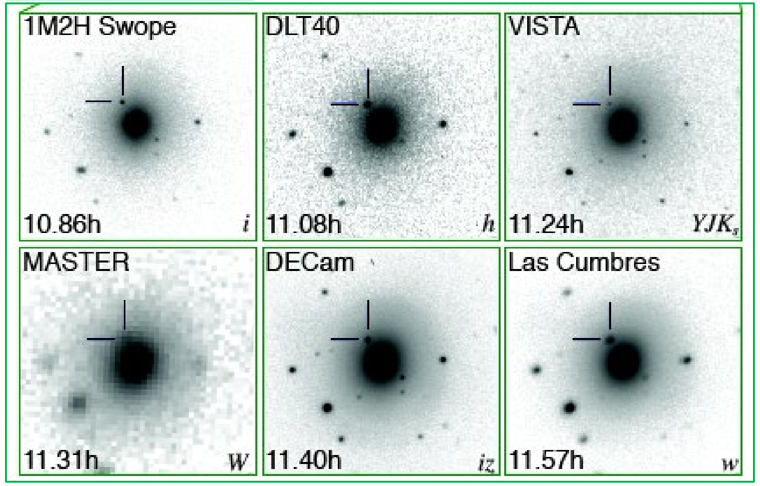
	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Counterparts



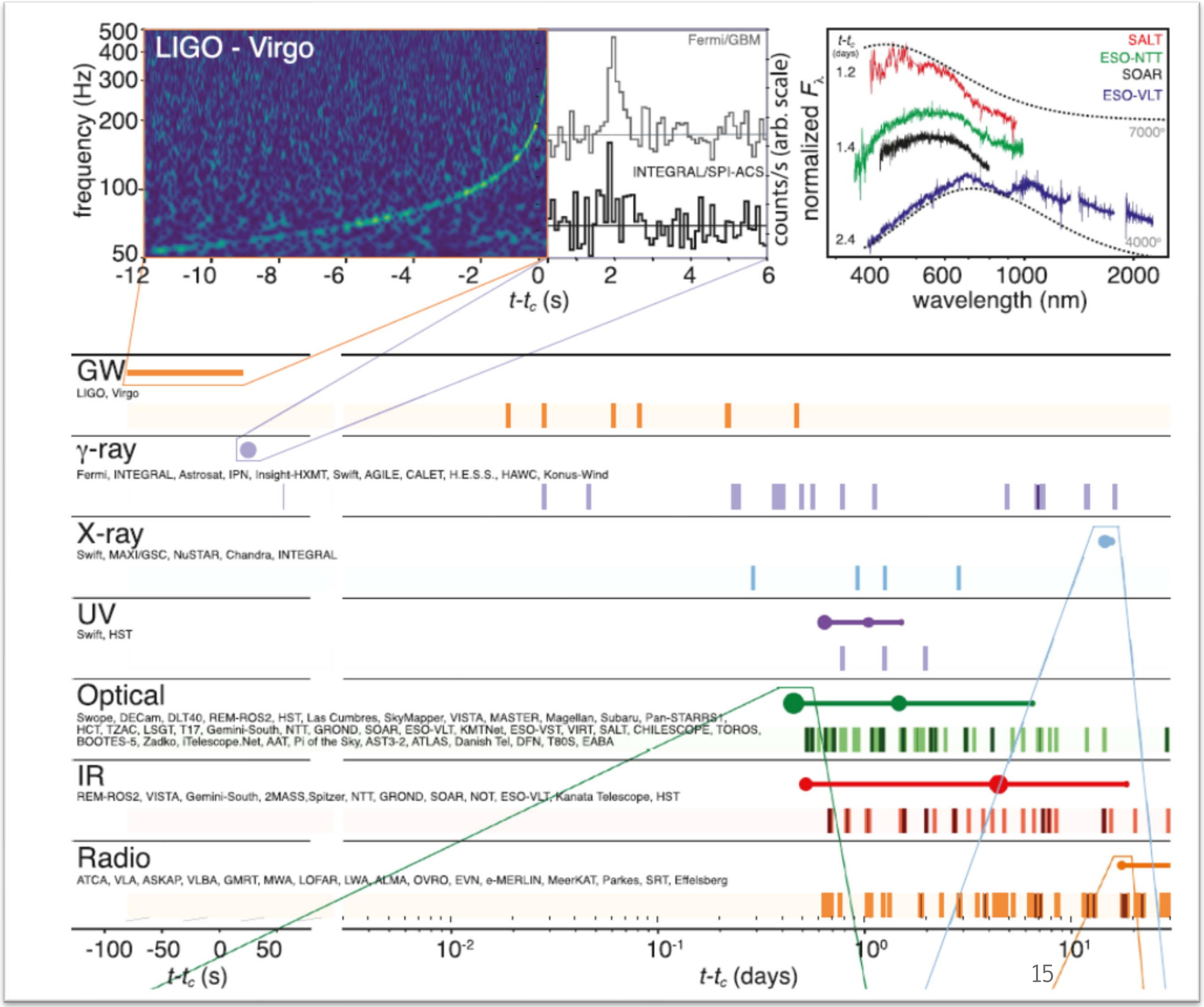


Coulter et al. 2017 *Yang et al. 2017* *Tanvir et al. 2017*



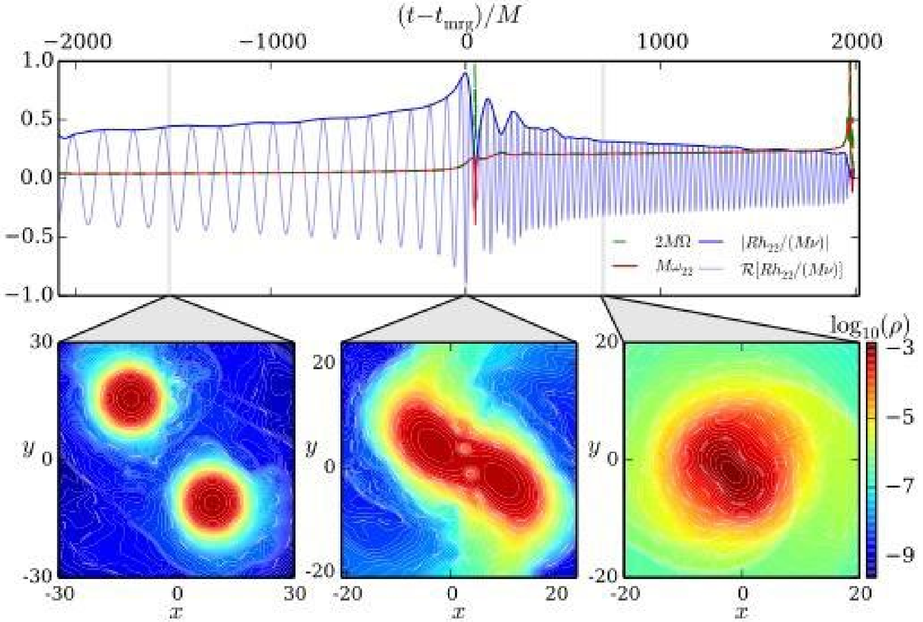
Lipunov et al. 2017 *Allam et al. 2017* *Accavi et al. 2017*

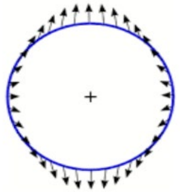
Observatories are still looking at this today.



[Phys. Rev. Letter **121**, 161101 (2018)](#) [Phys. Rev. Lett. **111**, 071101](#)

Nuclear matter EOS

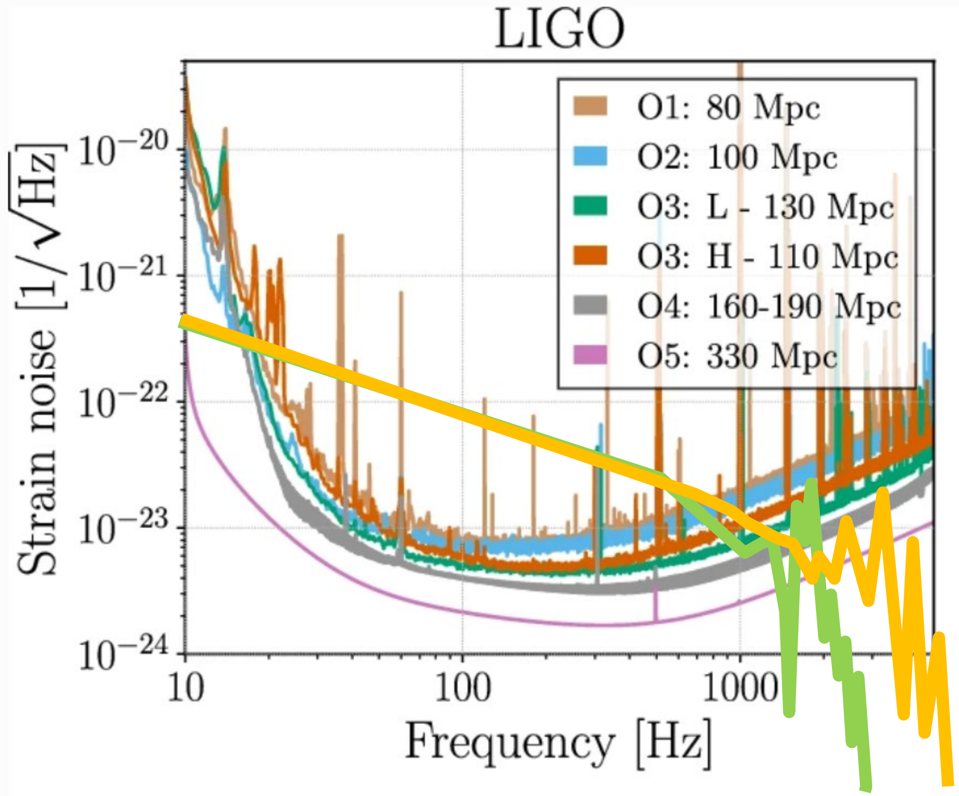


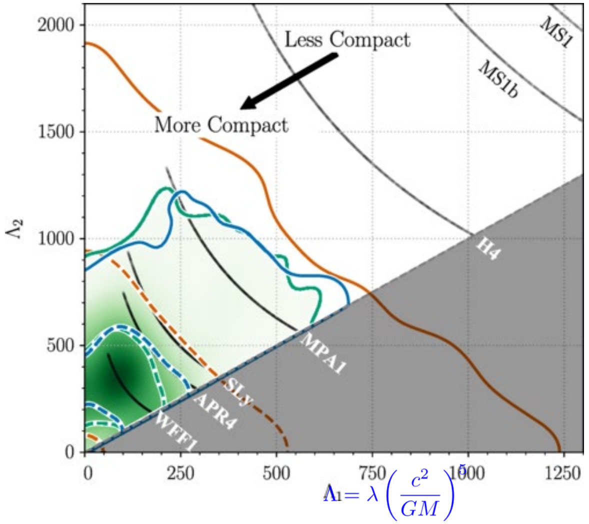


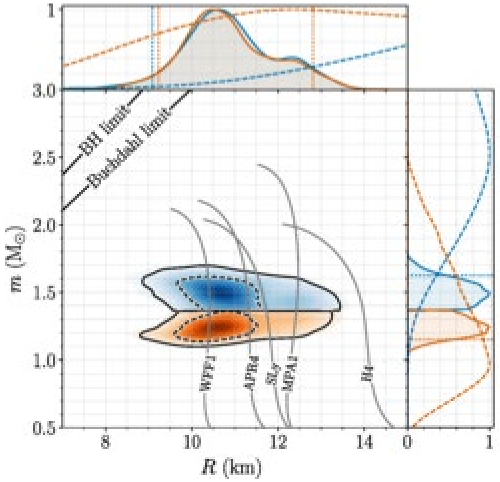
$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

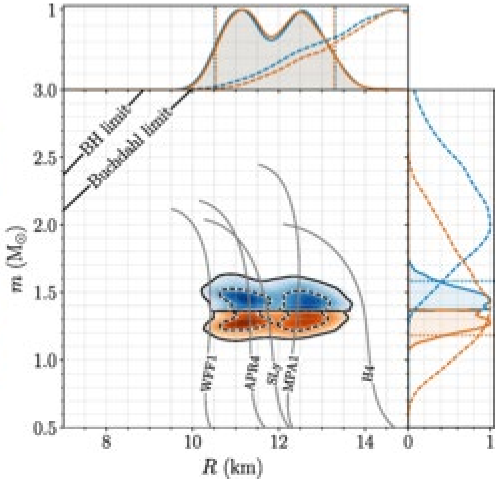
$$\lambda = \frac{2}{3} k_2 R^5$$

- Simplest effect: quadrupolar deformation induced by gravitational strain
- These tidal effects are imprinted on GW signal…
- … which contains information about nuclear matter Equation of State









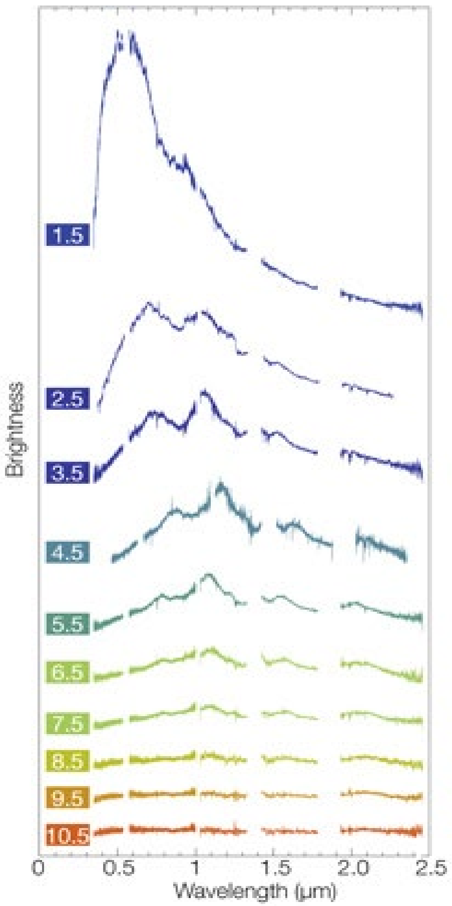
- «More compact» NS favoured
- «Too stiff» equation of state disfavoured
- But a large amount of information is coded in high frequency components of the signal
- **we will be able to look at this much better in the future**

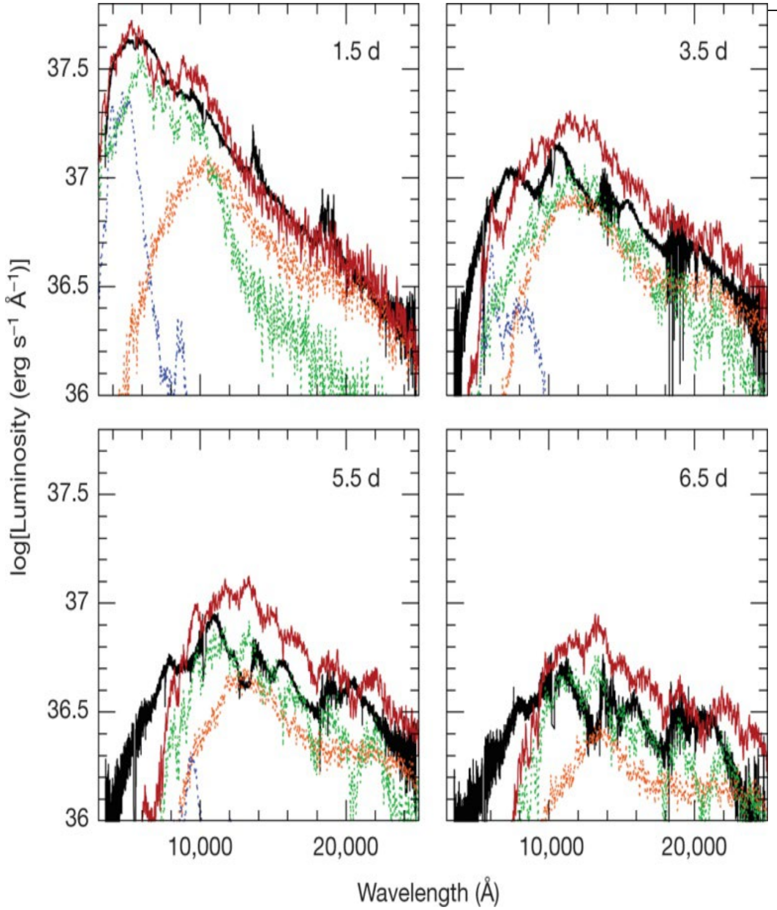
Kilonova

Siegel & Metzger 2017b, arXiv:1711.00868

Siegel & Metzger 2017a, PRL, arXiv:1705.05473

Credits: Eso/E. Pian et al./S. Smartt & ePessto

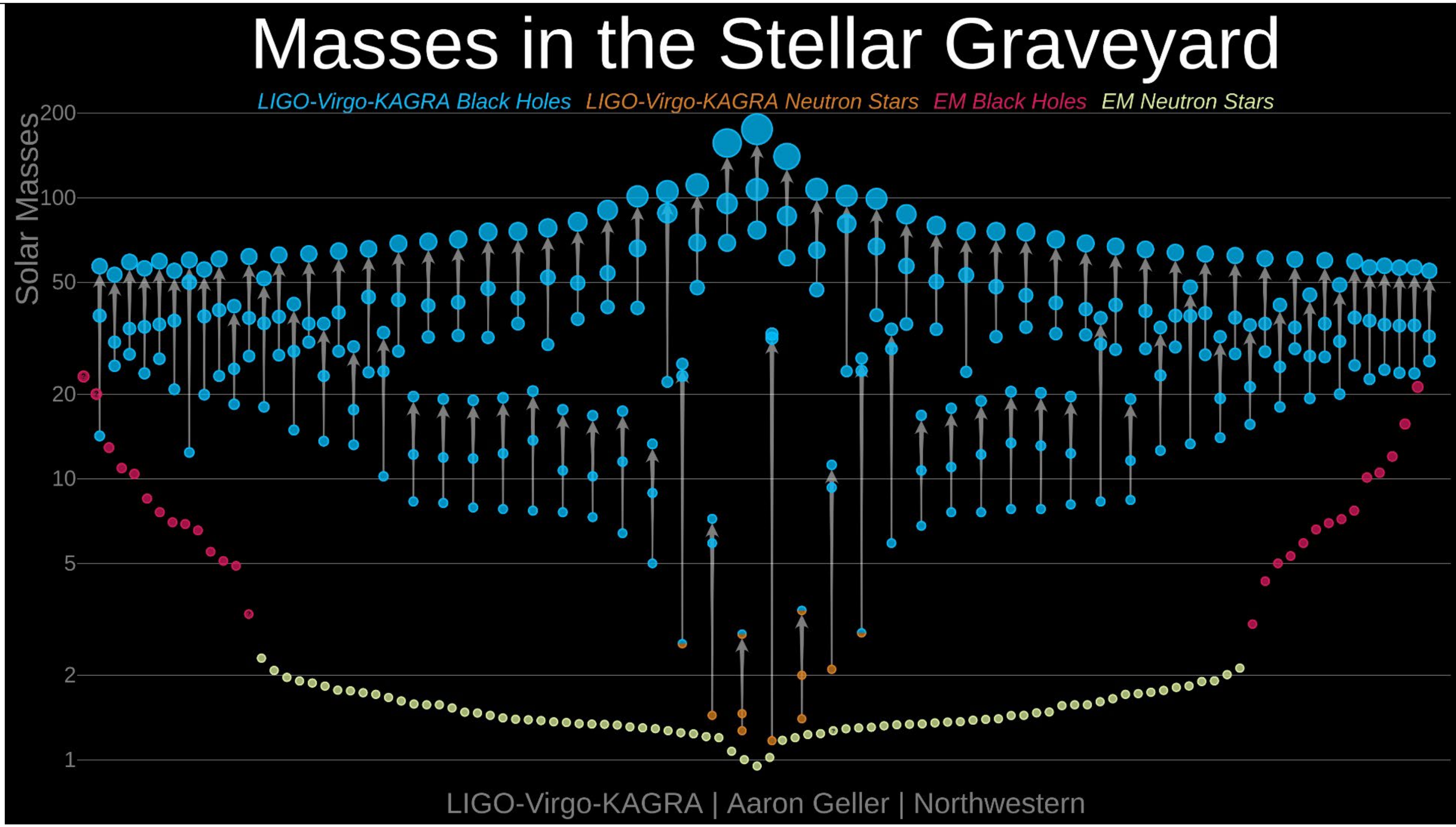




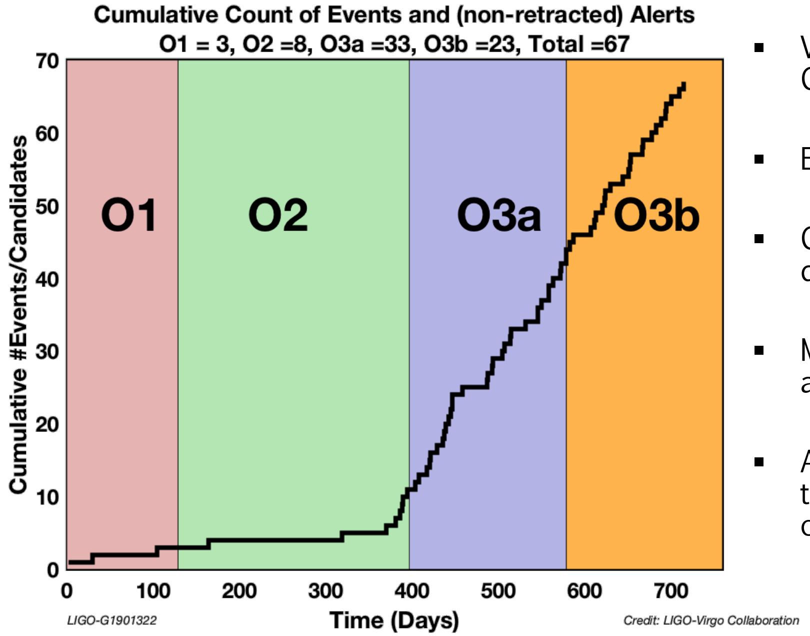
E Pian *et al. Nature* **551,** 67–70 (2017)
doi:10.1038/nature24298

Matter ejected in the post-merger phase undergoes r-process

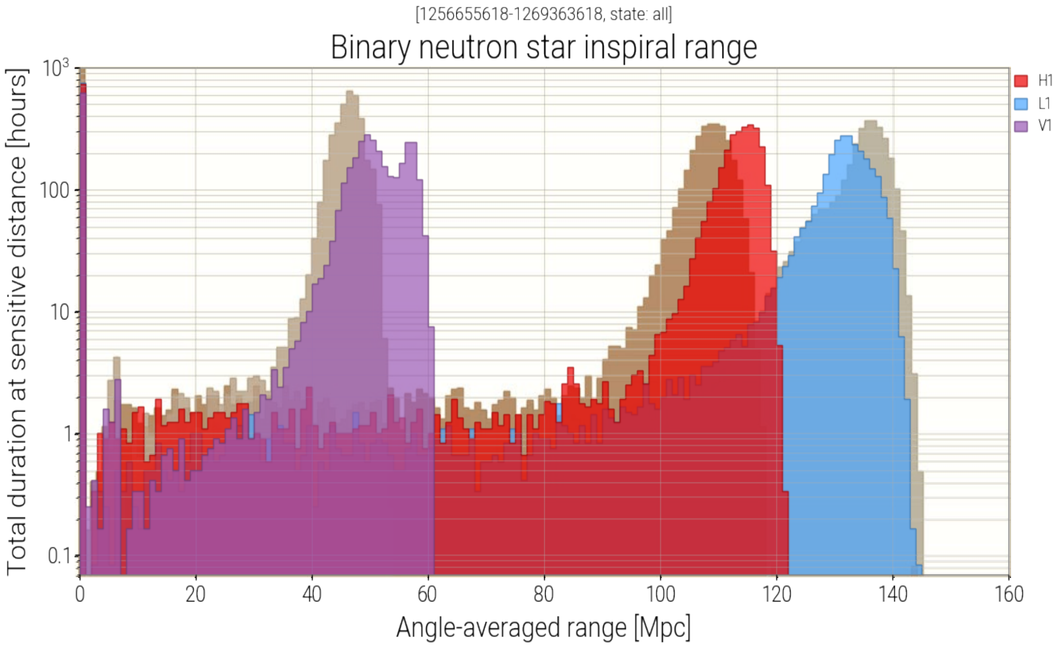
O3 RUN AND BEYOND

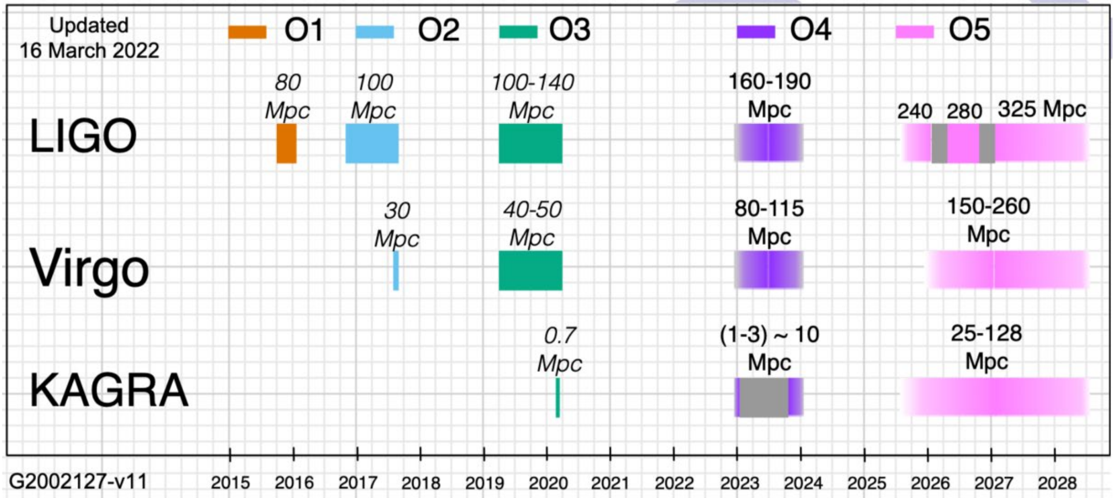


The last scientific run: **1st Nov 2019** to **27th Mar 2020**



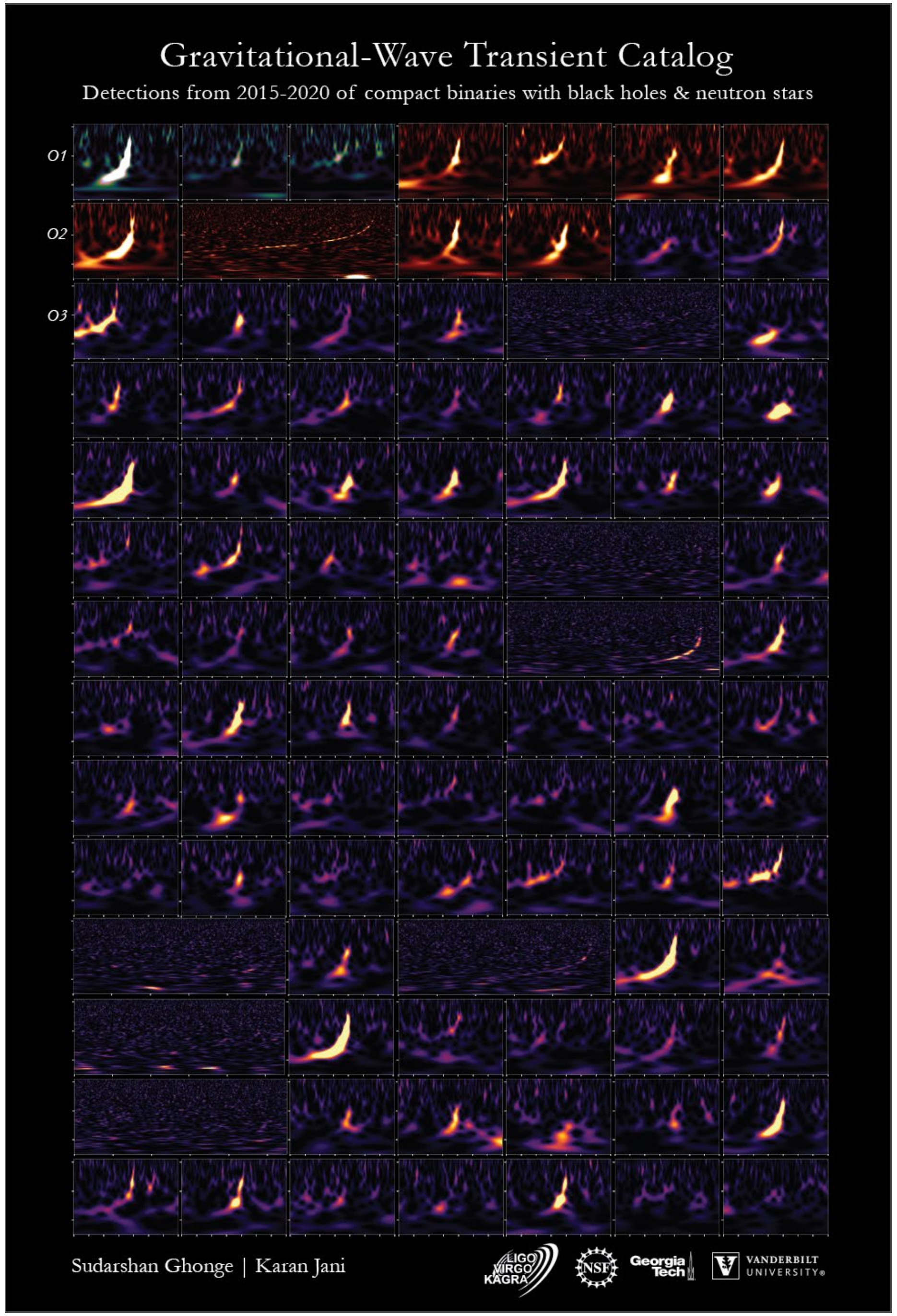
- Very productive run (in spite of COVID pandemy)
- Events rate scaled as expected
- Continuous improvement of detector sensitivities
- Many alerts sent to the astrophysics community
- A new scenario, which tested the capabilities of the LVK collaboration

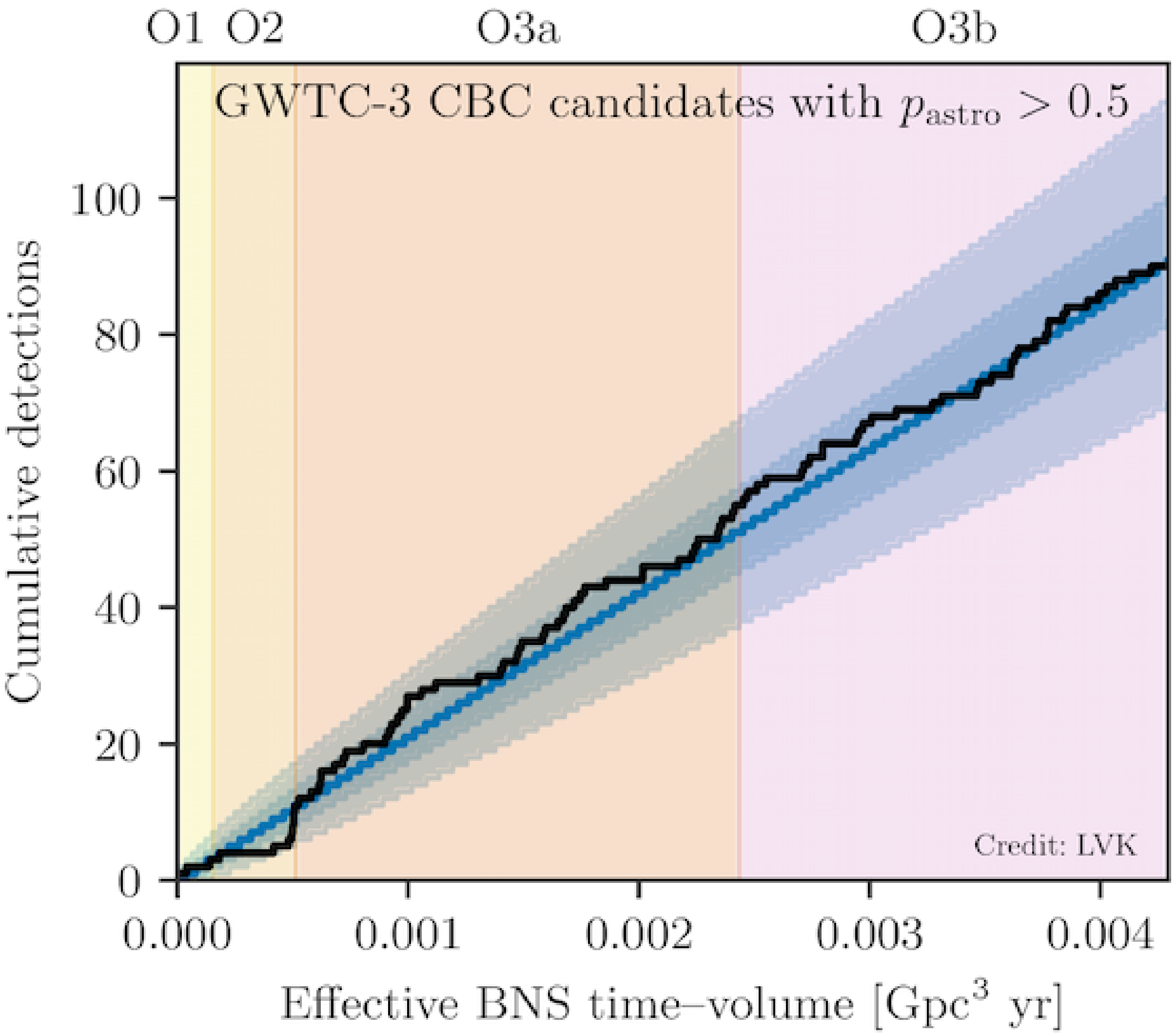




- Huge amount of information to elaborate (still in progress)
- We are now in an upgrade phase
- O4 run will change again the scenario:
  - about a factor 8 in events rate
  - New discoveries?

Gravitational-Wave Transient Catalog 3





O3b events

GW200220_061928
Most massive binary system in O3b with total mass = 148 M⊙

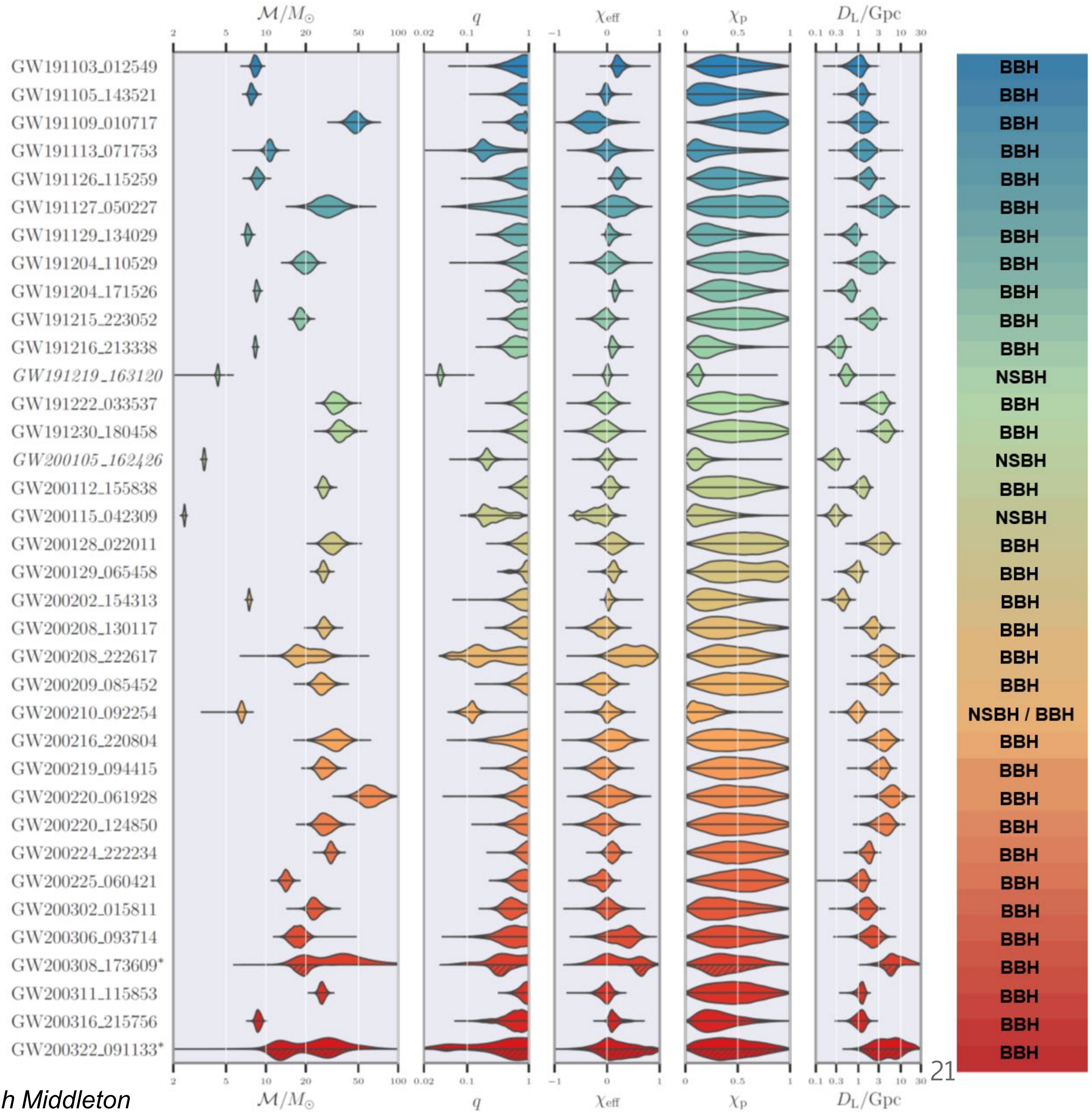
GW191219_163120
NSBH merger between a 1.17 M⊙ NS and 31.1 M⊙ BH. Most extreme mass ratio (q=0.038) measured to date

GW200115_042309
NSBH merger between a 1.44 M⊙ NS and 5.9 M⊙ BH

GW200210_092254
NSBH or BBH merger: less massive object has a mass of 2.83 M⊙

GW191109_010717
BBH merger which is very likely to have negative spin

GW191129_134029
Least massive definite BBH merger in O3b, with total mass = 17.6 M⊙



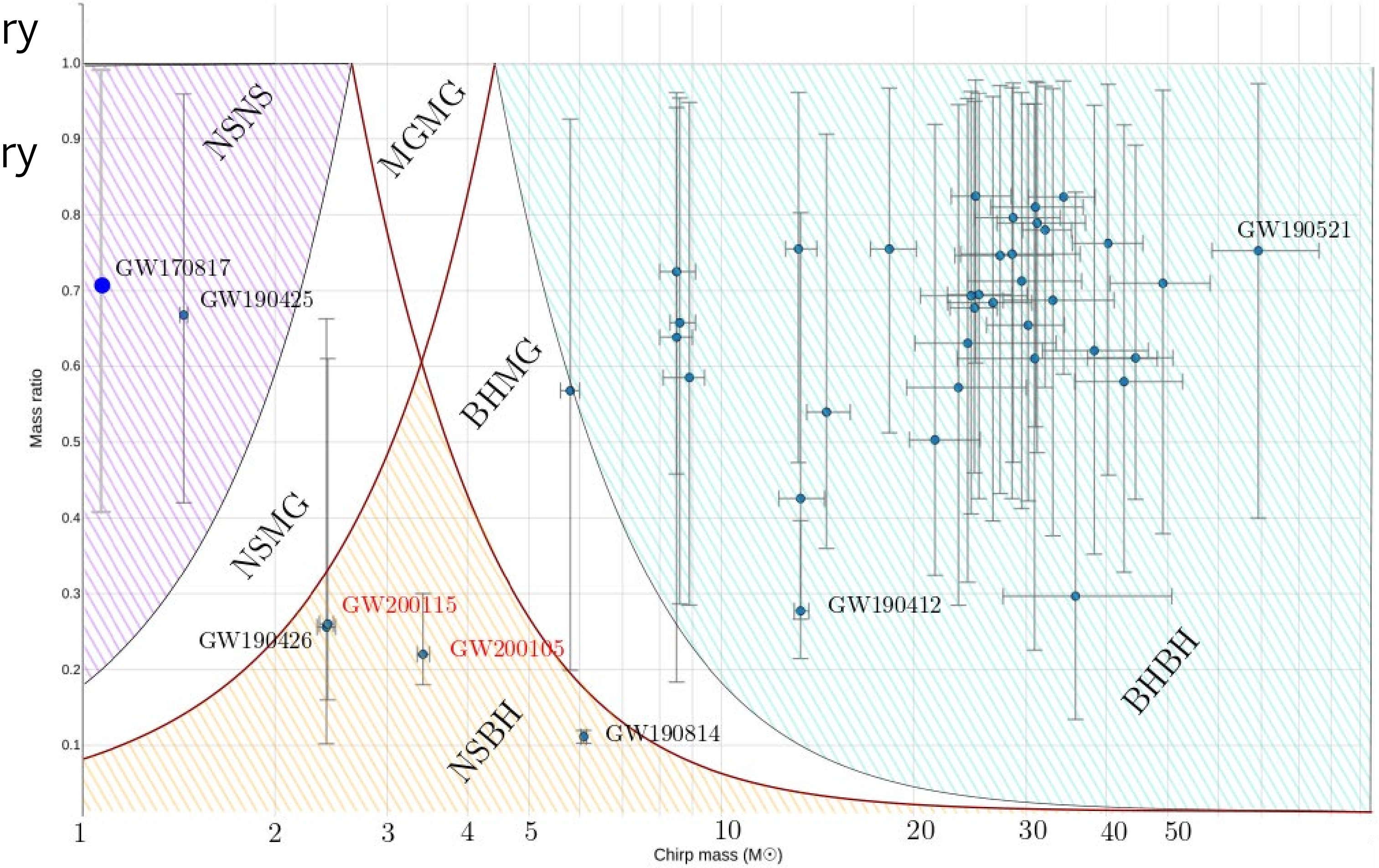
Credits: Martin Hendry, Hannah Middleton

Completing the CBC observations set

- ✓ **GW150914:** the first detection of a binary black hole coalescence
- ✓ **GW170817:** the first detection of a binary neutron star coalescence
- ✓ **GW200105/GW200115:** the first solid evidence of binary NS-BH system coalescence

The complete set of the compact binary coalescences we are expected to detect with earth-bound interferometers;

- Why are we confident about these detections?
- Why are such systems interesting?
- What we have learned?
- What we expect to learn in the future?

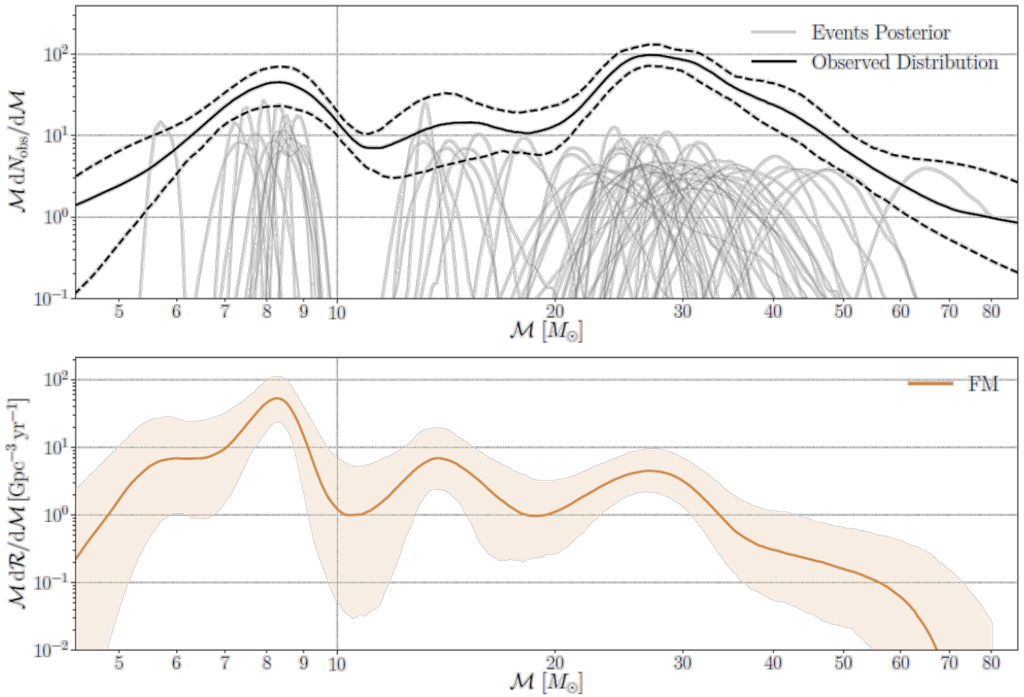


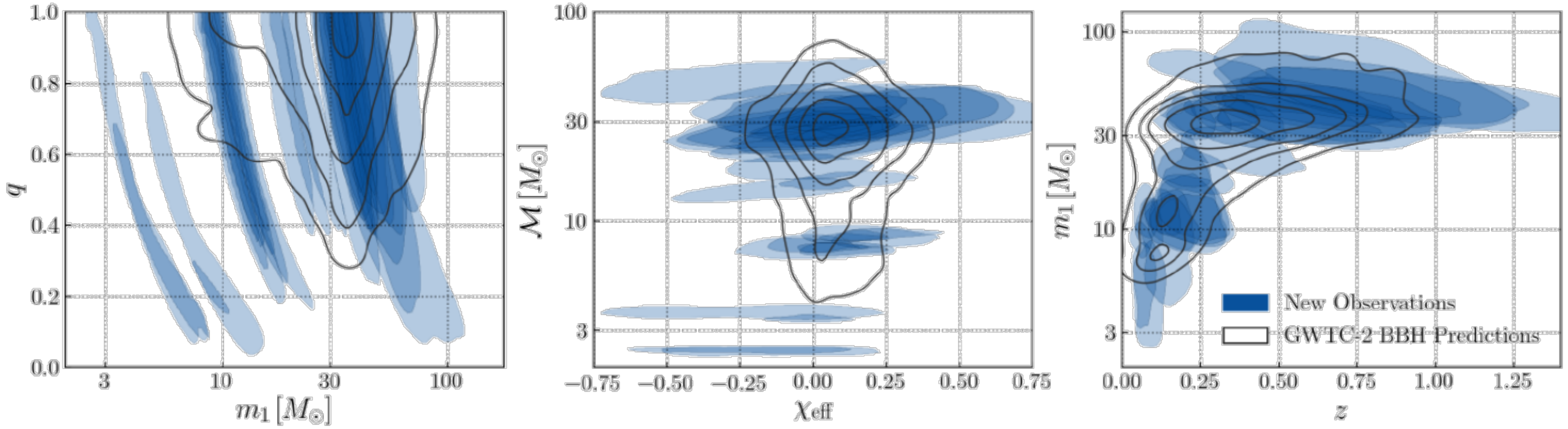
Credit: Chris North (Cardiff University). See http://catalog.cardiffgravity.org/

Companion papers: O3b Astrophysical Distribution

Entering in the «statistical information driven» regime

- NSBH binaries
- Lower mass gap
- NS mass distribution
- Substructure in BBH mass distribution
- BBH rate evolution with redshift





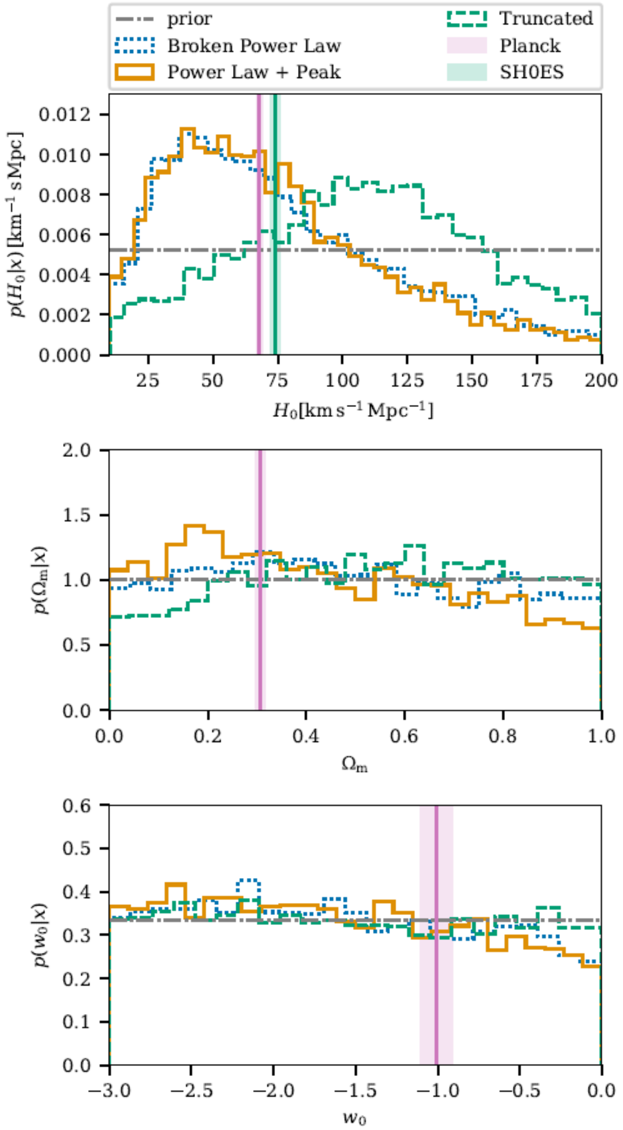
Companion papers: O3b Astrophysical Distribution

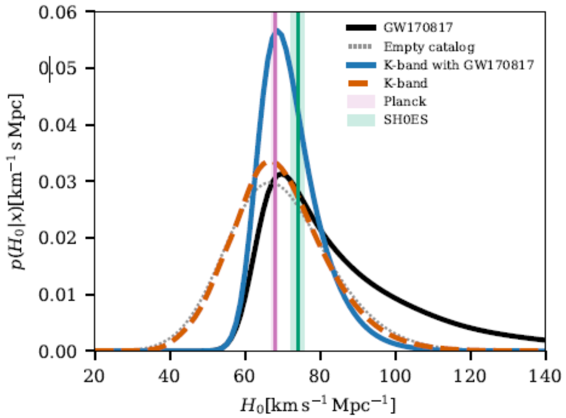
Constraints on cosmological parameters

- No «bright sirens» in O3
- Hierarchical inference
  Joint fit of cosmological parameters and BBH source population properties

$$m_i = \frac{m_i^{det}}{1 + z\,(D_L; H0, \Omega_m, w_0)}$$

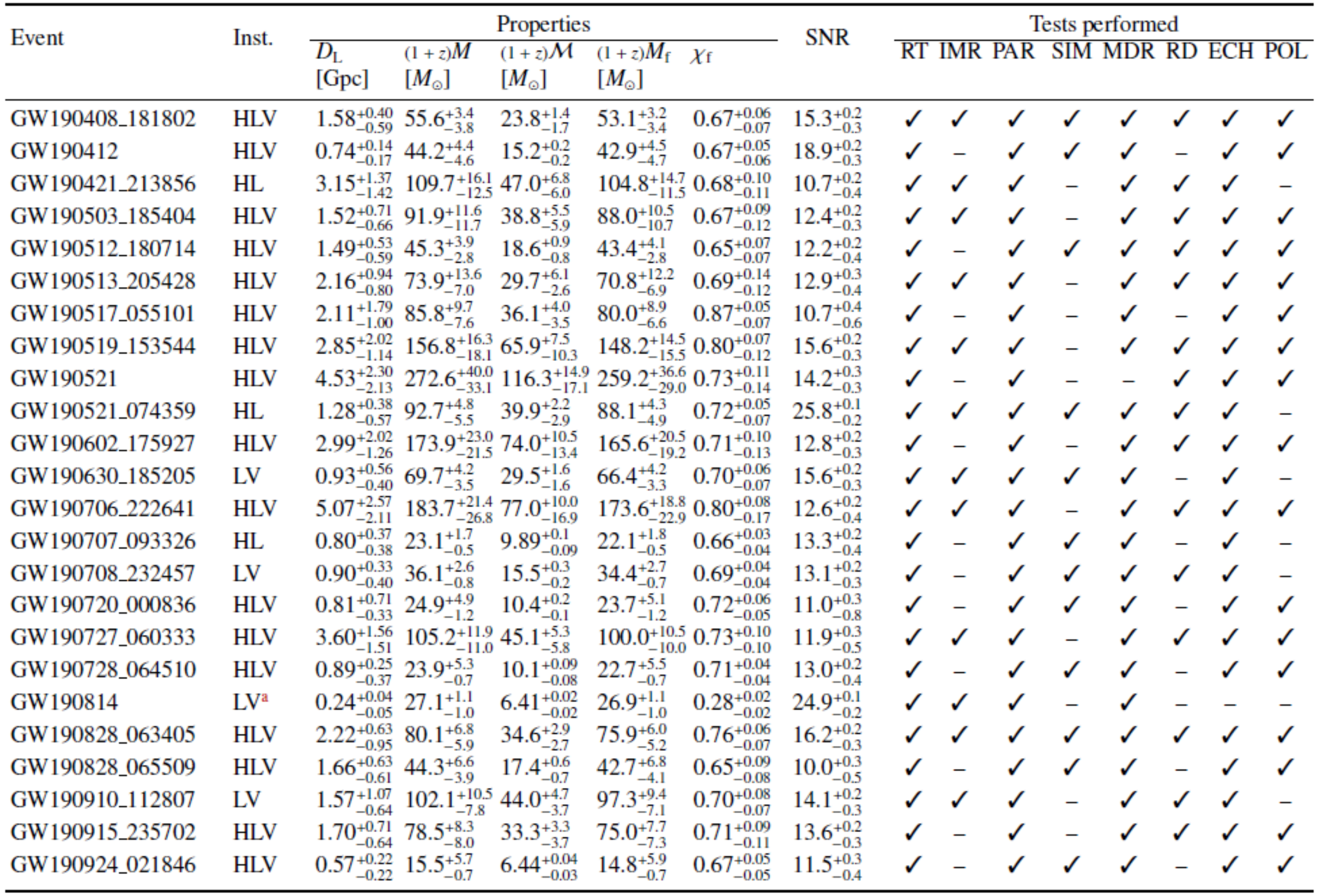
- Statistical galaxy catalog method
  Fix the source population, use statistical galaxy catalog information to provide redshift information





- 20% improvement on O2 for H_0
- Still dominated by systematic effects

O3a CBC Testing GR (Phys. Rev. D 103, 122002)



Event	Inst.	Properties					SNR	Tests performed							
		D_L [Gpc]	$(1+z)M$ $[M_\odot]$	$(1+z)\mathcal{M}$ $[M_\odot]$	$(1+z)M_f$ $[M_\odot]$	χ_f		RT	IMR	PAR	SIM	MDR	RD	ECH	POL
GW190408_181802	HLV	$1.58^{+0.40}_{-0.59}$	$55.6^{+3.4}_{-3.8}$	$23.8^{+1.4}_{-1.7}$	$53.1^{+3.2}_{-3.4}$	$0.67^{+0.06}_{-0.07}$	$15.3^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓	✓	✓	✓
GW190412	HLV	$0.74^{+0.14}_{-0.17}$	$44.2^{+4.4}_{-4.6}$	$15.2^{+0.2}_{-0.2}$	$42.9^{+4.5}_{-4.7}$	$0.67^{+0.05}_{-0.06}$	$18.9^{+0.2}_{-0.3}$	✓	–	✓	✓	✓	–	✓	✓
GW190421_213856	HL	$3.15^{+1.37}_{-1.42}$	$109.7^{+16.1}_{-12.5}$	$47.0^{+6.8}_{-6.0}$	$104.8^{+14.7}_{-11.5}$	$0.68^{+0.10}_{-0.11}$	$10.7^{+0.2}_{-0.4}$	✓	✓	✓	–	✓	✓	✓	–
GW190503_185404	HLV	$1.52^{+0.71}_{-0.66}$	$91.9^{+11.6}_{-11.7}$	$38.8^{+5.5}_{-5.9}$	$88.0^{+10.5}_{-10.7}$	$0.67^{+0.09}_{-0.12}$	$12.4^{+0.2}_{-0.3}$	✓	✓	✓	–	✓	✓	✓	✓
GW190512_180714	HLV	$1.49^{+0.53}_{-0.59}$	$45.3^{+3.9}_{-2.8}$	$18.6^{+0.9}_{-0.8}$	$43.4^{+4.1}_{-2.8}$	$0.65^{+0.07}_{-0.07}$	$12.2^{+0.2}_{-0.4}$	✓	–	✓	✓	✓	✓	✓	✓
GW190513_205428	HLV	$2.16^{+0.94}_{-0.80}$	$73.9^{+13.6}_{-7.0}$	$29.7^{+6.1}_{-2.6}$	$70.8^{+12.2}_{-6.9}$	$0.69^{+0.14}_{-0.12}$	$12.9^{+0.3}_{-0.4}$	✓	✓	✓	–	✓	✓	✓	✓
GW190517_055101	HLV	$2.11^{+1.79}_{-1.00}$	$85.8^{+9.7}_{-7.6}$	$36.1^{+4.0}_{-3.5}$	$80.0^{+8.9}_{-6.6}$	$0.87^{+0.05}_{-0.07}$	$10.7^{+0.4}_{-0.6}$	✓	–	✓	–	✓	–	✓	✓
GW190519_153544	HLV	$2.85^{+2.02}_{-1.14}$	$156.8^{+16.3}_{-18.1}$	$65.9^{+7.5}_{-10.3}$	$148.2^{+14.5}_{-15.5}$	$0.80^{+0.07}_{-0.12}$	$15.6^{+0.2}_{-0.3}$	✓	✓	✓	–	✓	✓	✓	✓
GW190521	HLV	$4.53^{+2.30}_{-2.13}$	$272.6^{+40.0}_{-33.1}$	$116.3^{+14.9}_{-17.1}$	$259.2^{+36.6}_{-29.0}$	$0.73^{+0.11}_{-0.14}$	$14.2^{+0.3}_{-0.3}$	✓	–	✓	–	–	✓	✓	✓
GW190521_074359	HL	$1.28^{+0.38}_{-0.57}$	$92.7^{+4.8}_{-5.5}$	$39.9^{+2.2}_{-2.9}$	$88.1^{+4.3}_{-4.9}$	$0.72^{+0.05}_{-0.07}$	$25.8^{+0.1}_{-0.2}$	✓	✓	✓	✓	✓	✓	✓	–
GW190602_175927	HLV	$2.99^{+2.02}_{-1.26}$	$173.9^{+23.0}_{-21.5}$	$74.0^{+10.5}_{-13.4}$	$165.6^{+20.5}_{-19.2}$	$0.71^{+0.10}_{-0.13}$	$12.8^{+0.2}_{-0.3}$	✓	–	✓	–	✓	✓	✓	✓
GW190630_185205	LV	$0.93^{+0.56}_{-0.40}$	$69.7^{+4.2}_{-3.5}$	$29.5^{+1.6}_{-1.6}$	$66.4^{+4.2}_{-3.3}$	$0.70^{+0.06}_{-0.07}$	$15.6^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓	–	✓	–
GW190706_222641	HLV	$5.07^{+2.57}_{-2.11}$	$183.7^{+21.4}_{-26.8}$	$77.0^{+10.0}_{-16.9}$	$173.6^{+18.8}_{-22.9}$	$0.80^{+0.08}_{-0.17}$	$12.6^{+0.2}_{-0.4}$	✓	✓	✓	–	✓	✓	✓	✓
GW190707_093326	HL	$0.80^{+0.37}_{-0.38}$	$23.1^{+1.7}_{-0.5}$	$9.89^{+0.1}_{-0.09}$	$22.1^{+1.8}_{-0.5}$	$0.66^{+0.03}_{-0.04}$	$13.3^{+0.2}_{-0.4}$	✓	–	✓	✓	✓	–	✓	–
GW190708_232457	LV	$0.90^{+0.33}_{-0.40}$	$36.1^{+2.6}_{-0.8}$	$15.5^{+0.3}_{-0.2}$	$34.4^{+2.7}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$13.1^{+0.2}_{-0.3}$	✓	–	✓	✓	✓	✓	✓	–
GW190720_000836	HLV	$0.81^{+0.71}_{-0.33}$	$24.9^{+4.9}_{-1.2}$	$10.4^{+0.2}_{-0.1}$	$23.7^{+5.1}_{-1.2}$	$0.72^{+0.06}_{-0.05}$	$11.0^{+0.3}_{-0.8}$	✓	–	✓	✓	✓	–	✓	✓
GW190727_060333	HLV	$3.60^{+1.56}_{-1.51}$	$105.2^{+11.9}_{-11.0}$	$45.1^{+5.3}_{-5.8}$	$100.0^{+10.5}_{-10.0}$	$0.73^{+0.10}_{-0.10}$	$11.9^{+0.3}_{-0.5}$	✓	✓	✓	–	✓	✓	✓	✓
GW190728_064510	HLV	$0.89^{+0.25}_{-0.37}$	$23.9^{+5.3}_{-0.7}$	$10.1^{+0.09}_{-0.08}$	$22.7^{+5.5}_{-0.7}$	$0.71^{+0.04}_{-0.04}$	$13.0^{+0.2}_{-0.4}$	✓	–	✓	✓	✓	–	✓	✓
GW190814	LV[a]	$0.24^{+0.04}_{-0.05}$	$27.1^{+1.1}_{-1.0}$	$6.41^{+0.02}_{-0.02}$	$26.9^{+1.1}_{-1.0}$	$0.28^{+0.02}_{-0.02}$	$24.9^{+0.1}_{-0.2}$	✓	✓	✓	–	✓	–	–	–
GW190828_063405	HLV	$2.22^{+0.63}_{-0.95}$	$80.1^{+6.8}_{-5.9}$	$34.6^{+2.9}_{-2.7}$	$75.9^{+6.0}_{-5.2}$	$0.76^{+0.06}_{-0.07}$	$16.2^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓	✓	✓	✓
GW190828_065509	HLV	$1.66^{+0.63}_{-0.61}$	$44.3^{+6.6}_{-3.9}$	$17.4^{+0.6}_{-0.7}$	$42.7^{+6.8}_{-4.1}$	$0.65^{+0.09}_{-0.08}$	$10.0^{+0.3}_{-0.5}$	✓	–	✓	✓	✓	–	✓	✓
GW190910_112807	LV	$1.57^{+1.07}_{-0.64}$	$102.1^{+10.5}_{-7.8}$	$44.0^{+4.7}_{-3.7}$	$97.3^{+9.4}_{-7.1}$	$0.70^{+0.08}_{-0.07}$	$14.1^{+0.2}_{-0.3}$	✓	✓	✓	–	✓	✓	✓	–
GW190915_235702	HLV	$1.70^{+0.71}_{-0.64}$	$78.5^{+8.3}_{-8.0}$	$33.3^{+3.3}_{-3.7}$	$75.0^{+7.7}_{-7.3}$	$0.71^{+0.09}_{-0.11}$	$13.6^{+0.2}_{-0.3}$	✓	–	✓	–	✓	✓	✓	✓
GW190924_021846	HLV	$0.57^{+0.22}_{-0.22}$	$15.5^{+5.7}_{-0.7}$	$6.44^{+0.04}_{-0.03}$	$14.8^{+5.9}_{-0.7}$	$0.67^{+0.05}_{-0.05}$	$11.5^{+0.3}_{-0.4}$	✓	–	✓	✓	✓	–	✓	✓

- *RT Residual test*
- *IMR Inspiral Merger Ringdown consistency test*
- *PAR parameterized test of GW generation*
- *SIM Spin Induced Moments:*

$$Q = -\kappa\chi^2 m^3$$

- *MDR Modified Dispersion Relations:*

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

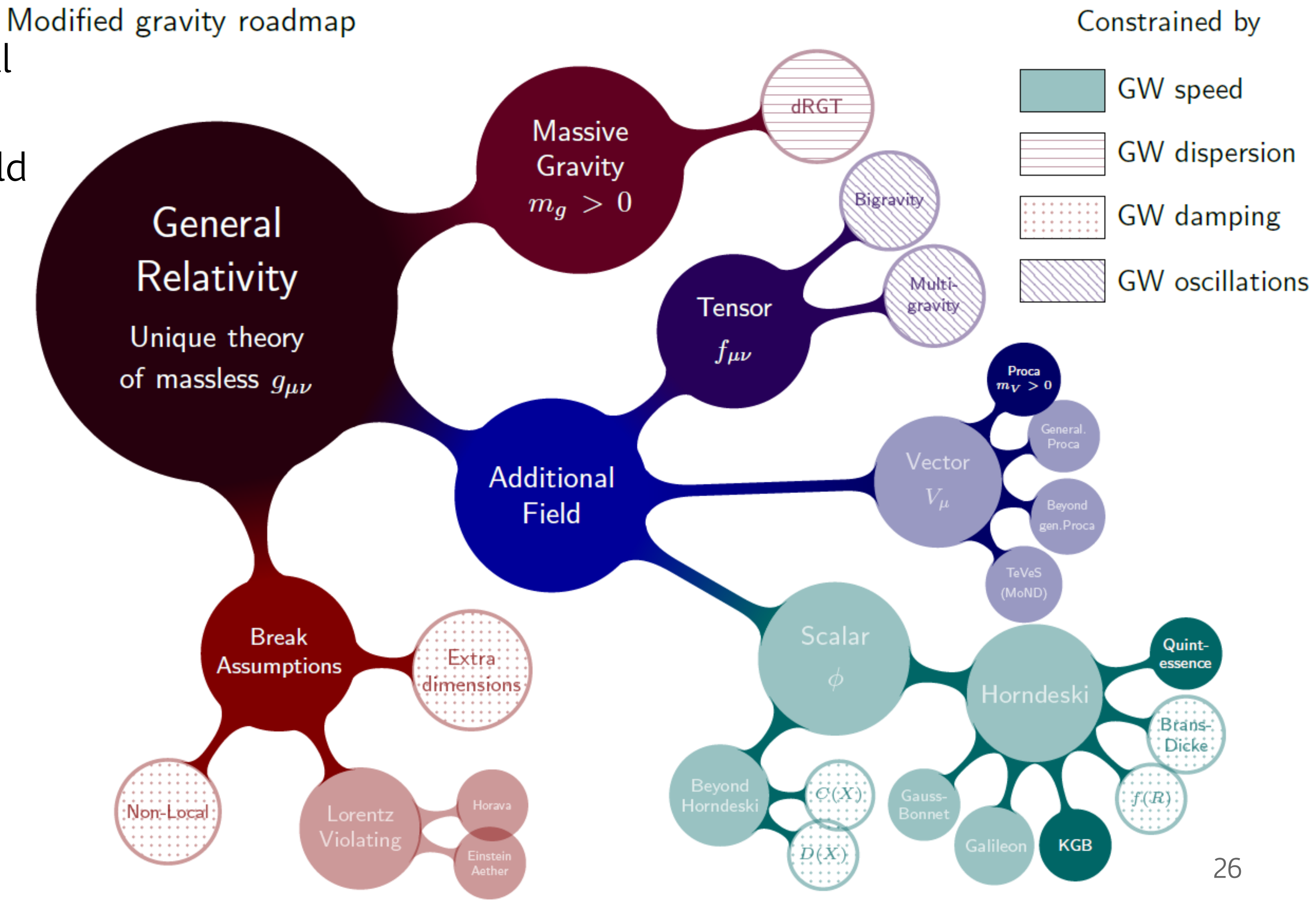
- *RD Ringdown*
- *ECH Echoes*
- *POL Polarization content*

Front. Astron. Space Sci. 5:44 (2018)

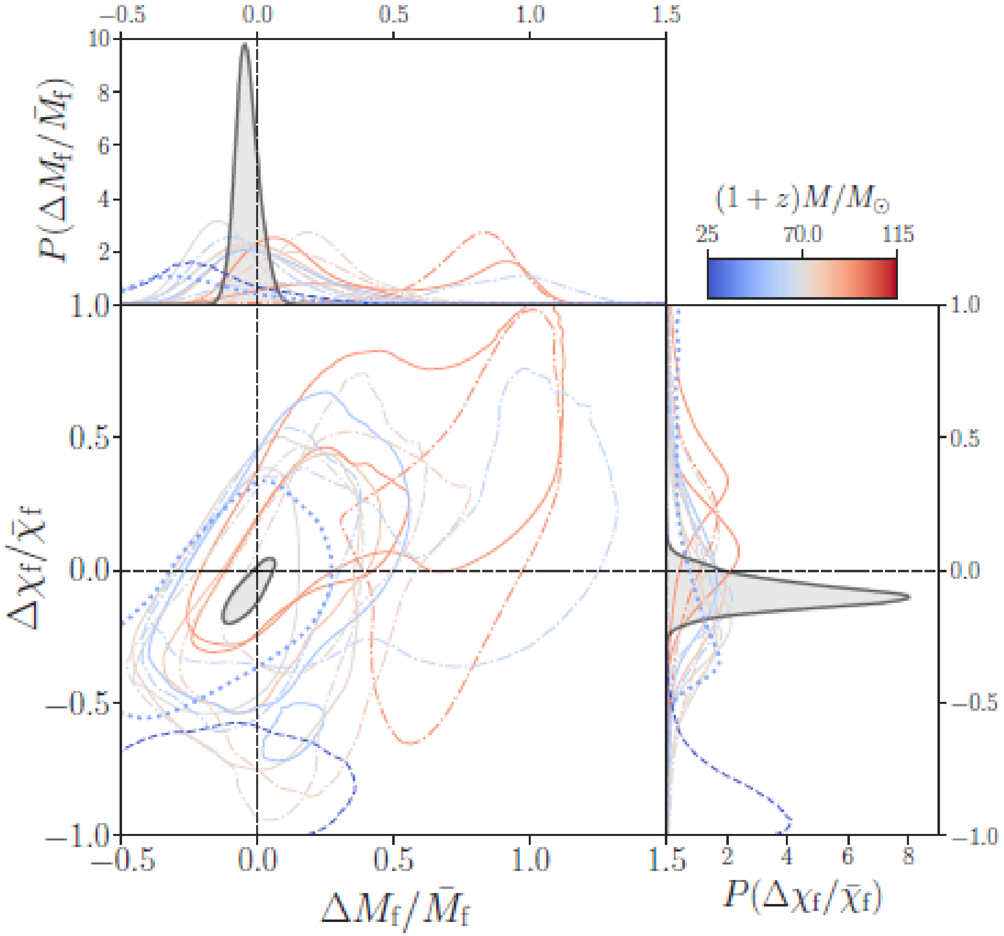
Modified gravity roadmap

GWs are a new tool to test General Relativity:

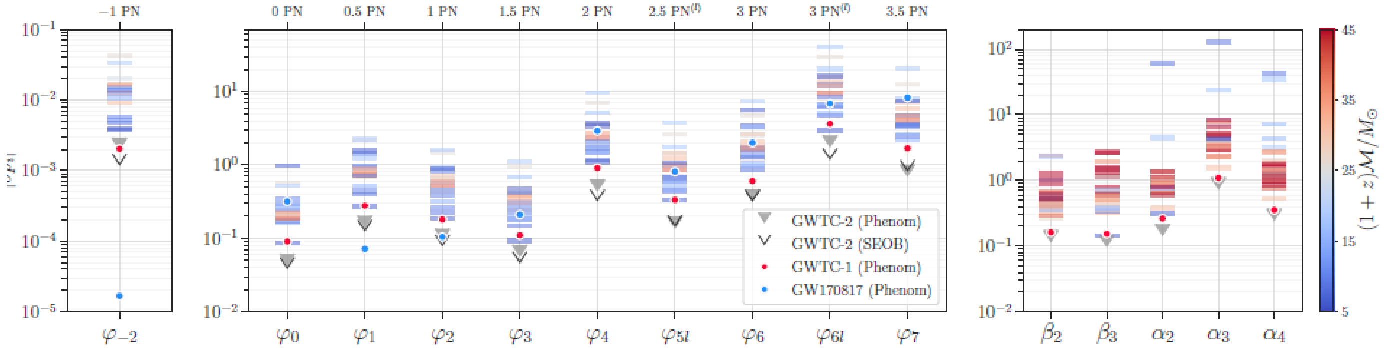
- Checks in dynamical, strong field regimes
- Looking at signals generated in the very early Universe
- Multimessenger:
  - Standard sirens
  - Propagation speed
  - Damping
  - Additional polarizations
  - GW oscillations



O3a CBC Testing GR (Phys. Rev. D 103, 122002)

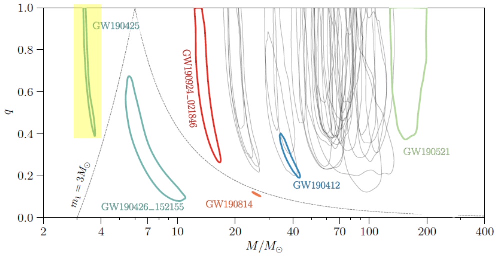


- Improved constraints on Lorentz violation
- Graviton mass $m_g \leq 1.76 \times 10^{-23}\ \mathrm{eV}/c^2$
- Constraints on post-Newtonian parameters improved by a factor 2



GW190425: Observation of a Compact Binary Coalescence with total mass $\sim 3.4 M_\odot$

AJL 892 (2020) L3



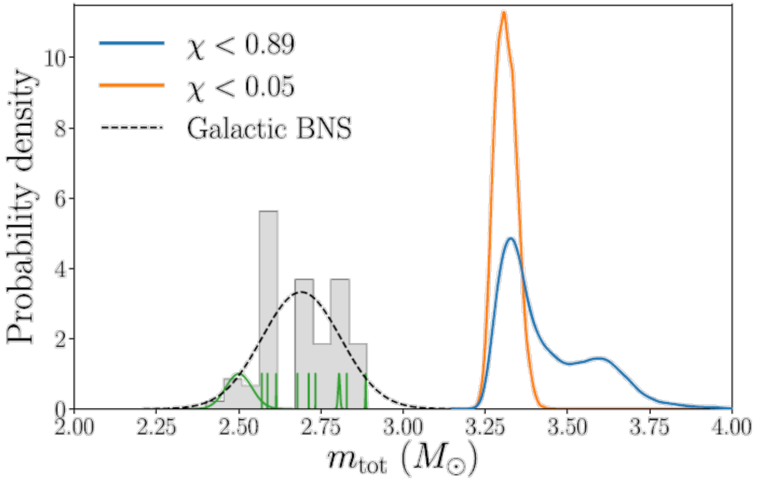
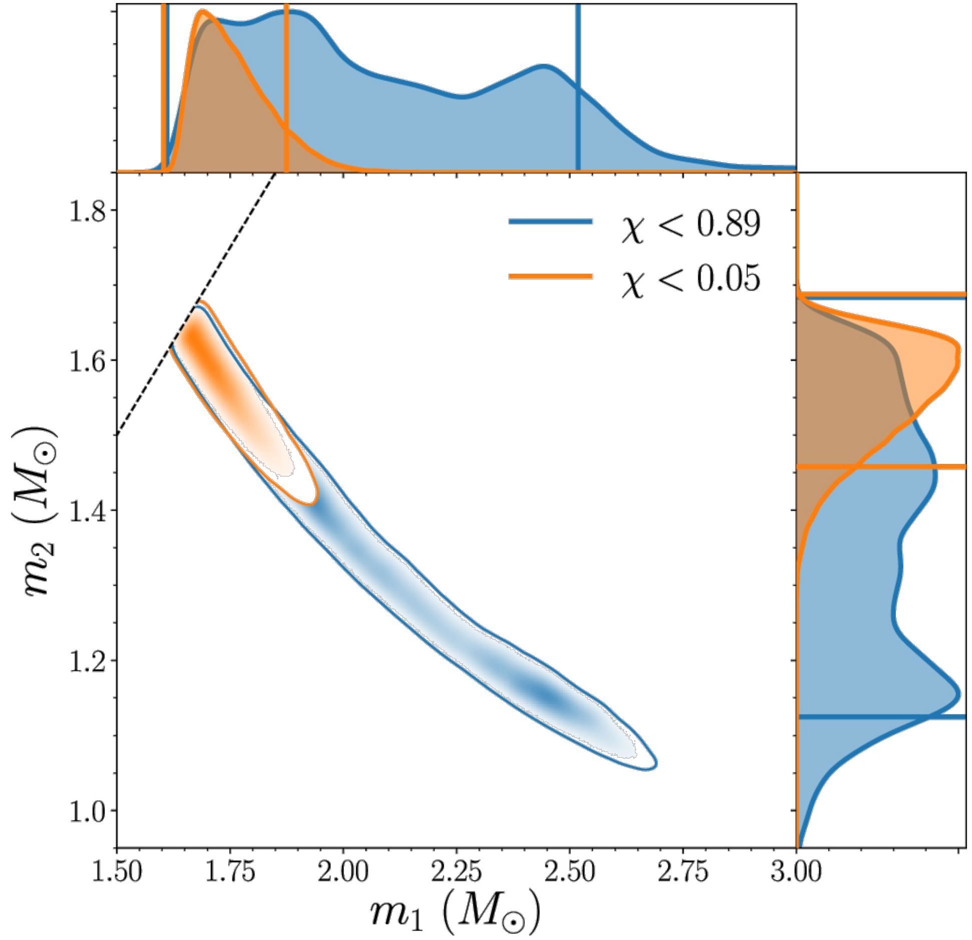
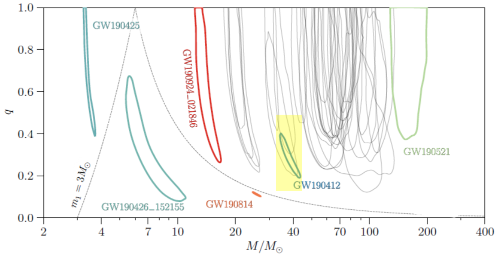


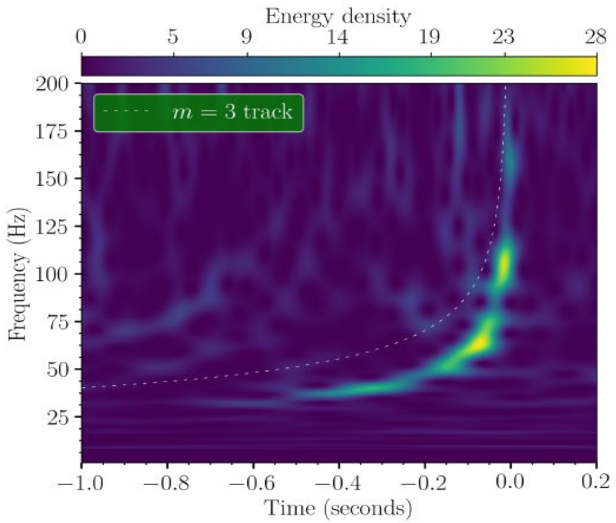
Figure 5. Total system masses for GW190425 under different spin priors, and those for the 10 Galactic BNSs from Farrow et al. (2019) that are expected to merge within a Hubble time. The distribution of the total masses of the latter is shown and fit using a normal distribution shown by the dashed black curve. The green curves are for individual Galactic BNS total mass distributions rescaled to the same ordinate axis height of 1.



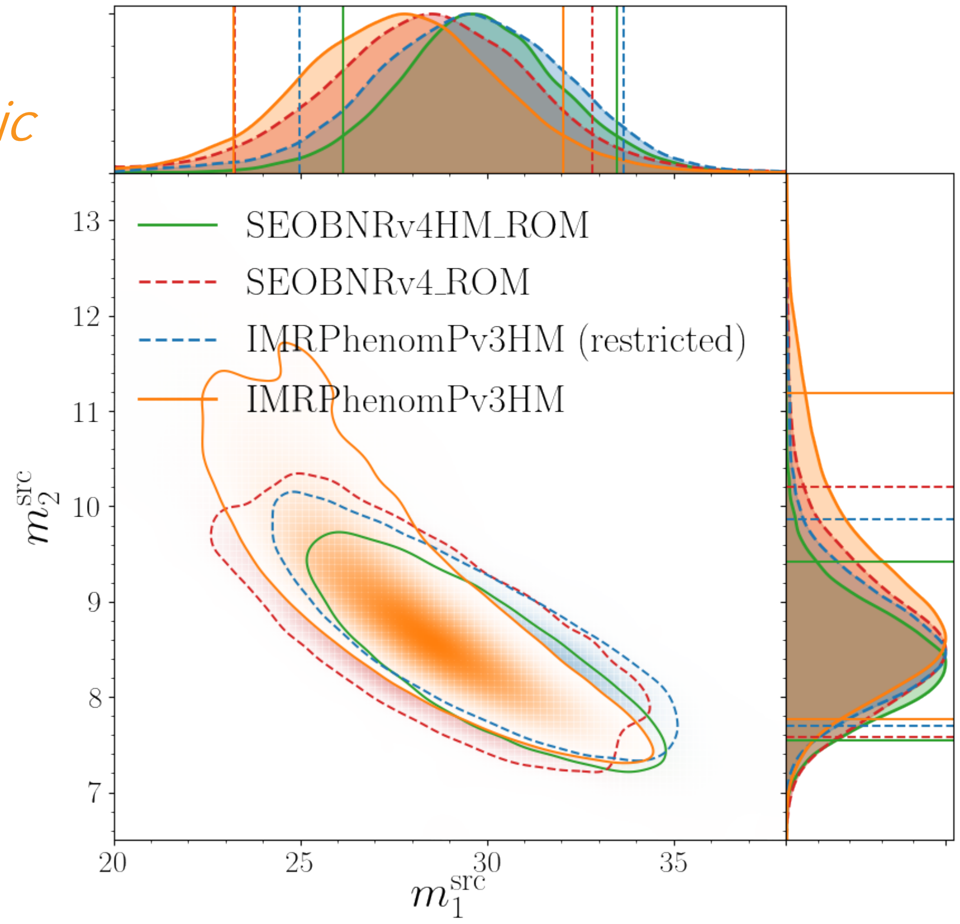
- *Most likely BNS system: another BNS detection but…*
- *…no solid electromagnetic counterpart*
- *Total mass* $3.4^{+0.3}_{-0.1} M_\odot$ $\quad D_L = 159^{+69}_{-71}\ Mpc$
- *Significantly different from the known population of Galactic BNS systems*
- *Cannot rule out BBH or BHNS*

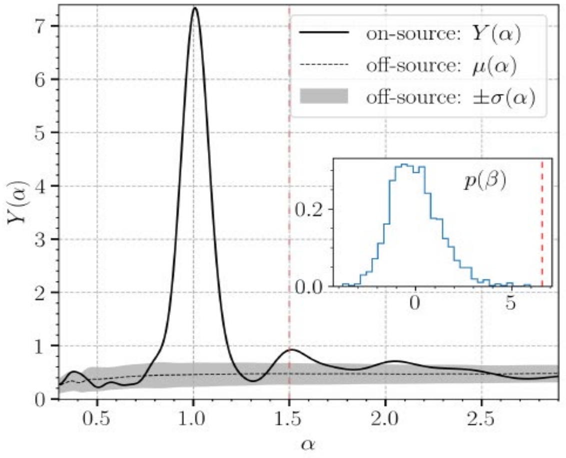
GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric masses
Phys. Rev. D 102, 043015 (2020)

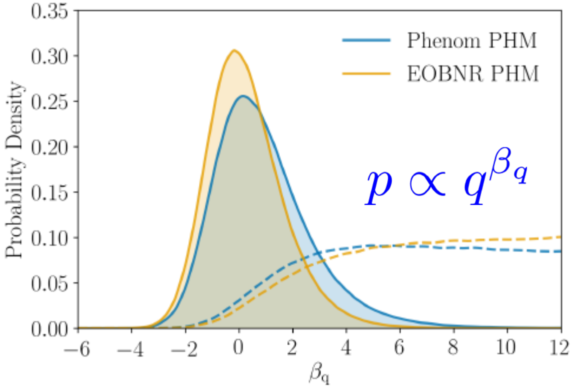




- *Evidence for (3,3) multipole: $f_\alpha(t) = \alpha f_{22}(t)$*
- *Tighter bounds on intrinsic source parameters*
- *Bounds on abundances*
- *Consistency with GR*

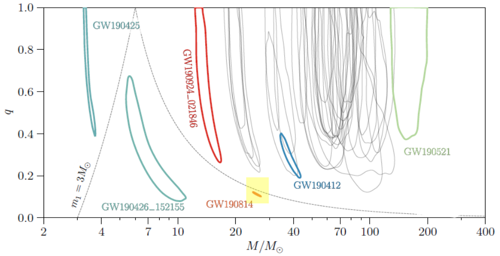


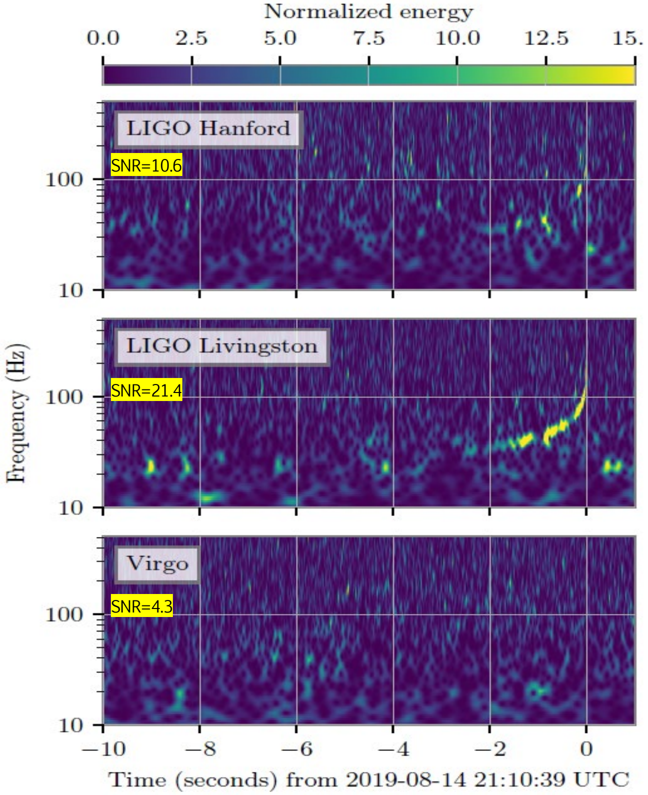




$p \propto q^{\beta_q}$

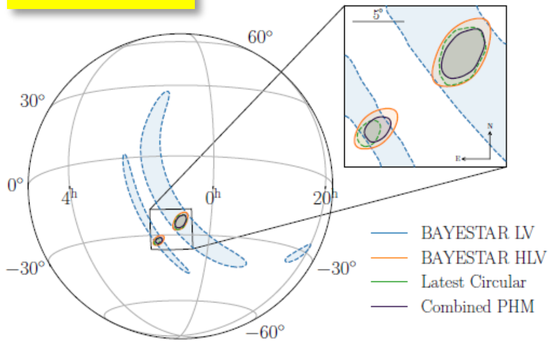
GW190814: Gravitational Waves from the Coalescence of a 23 $M_\odot$ Compact Object
Abbott et al 2020 ApJL 896 L44



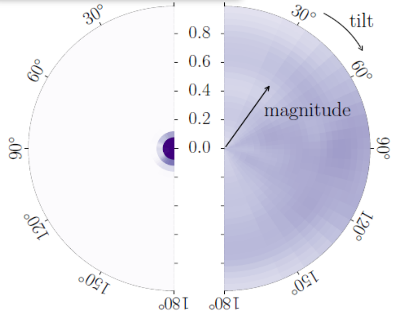


- *Network SNR=25*
- *No em counterpart*
- $q = 0.112^{+0.008}_{-0.009}$
- *NSBH or BBH?*
- *Multipole evidence*
- *No GR violation evidence*
- *Challenge for formation models*

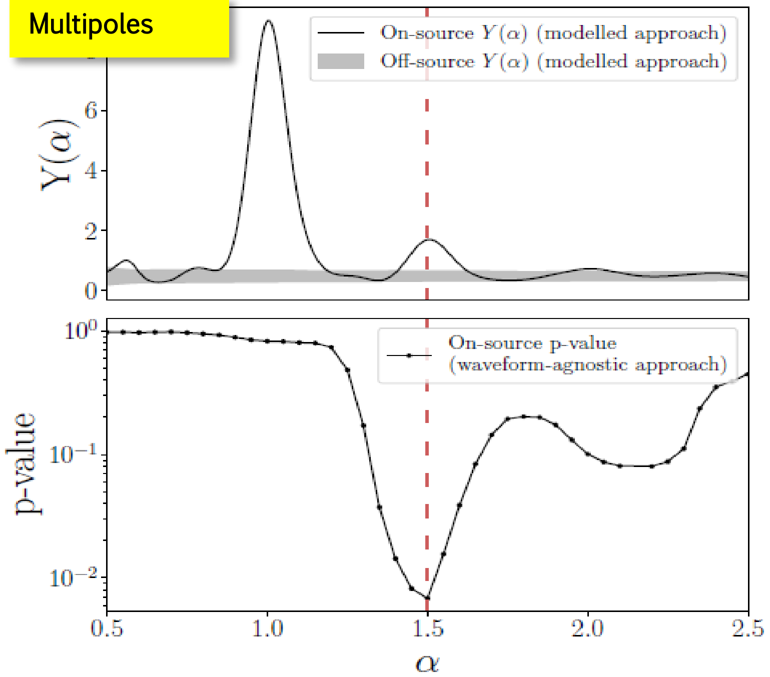
Localisation



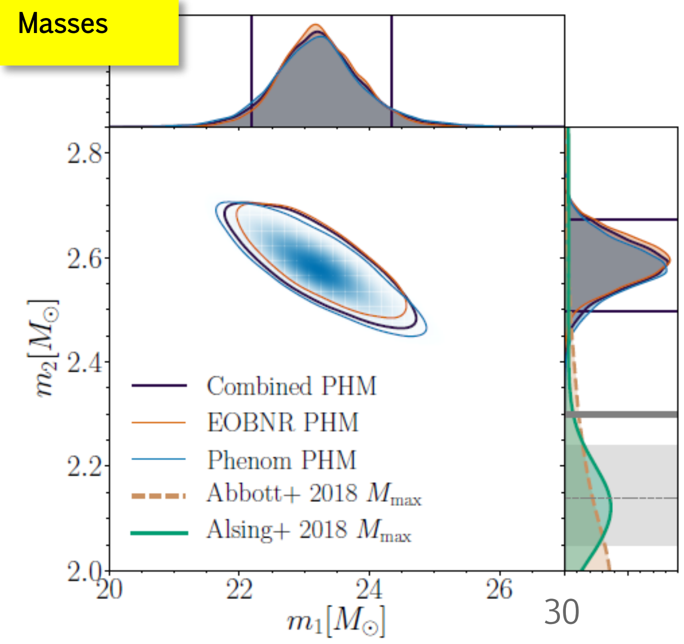
Spin posterior



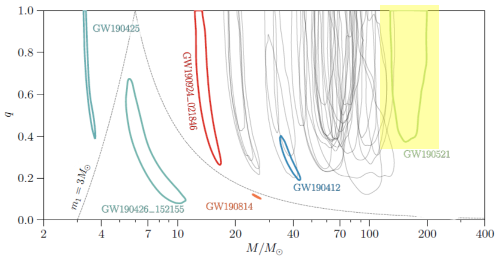
Multipoles

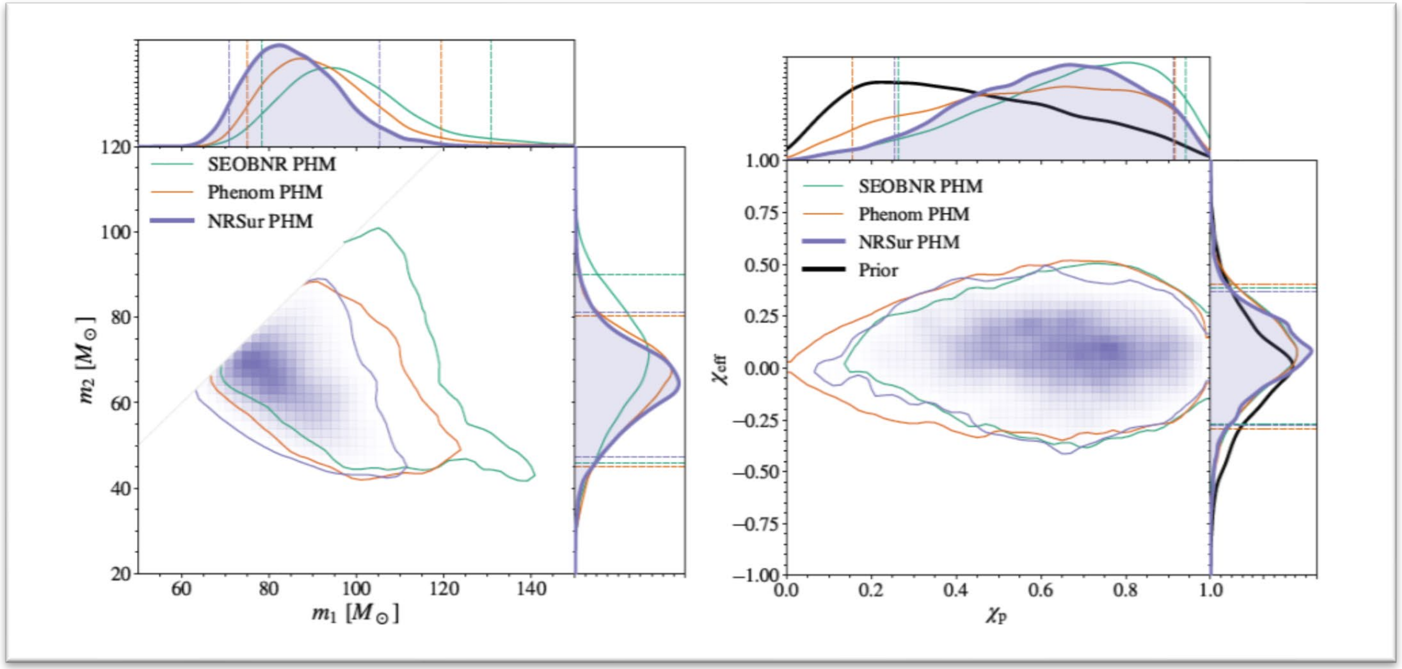


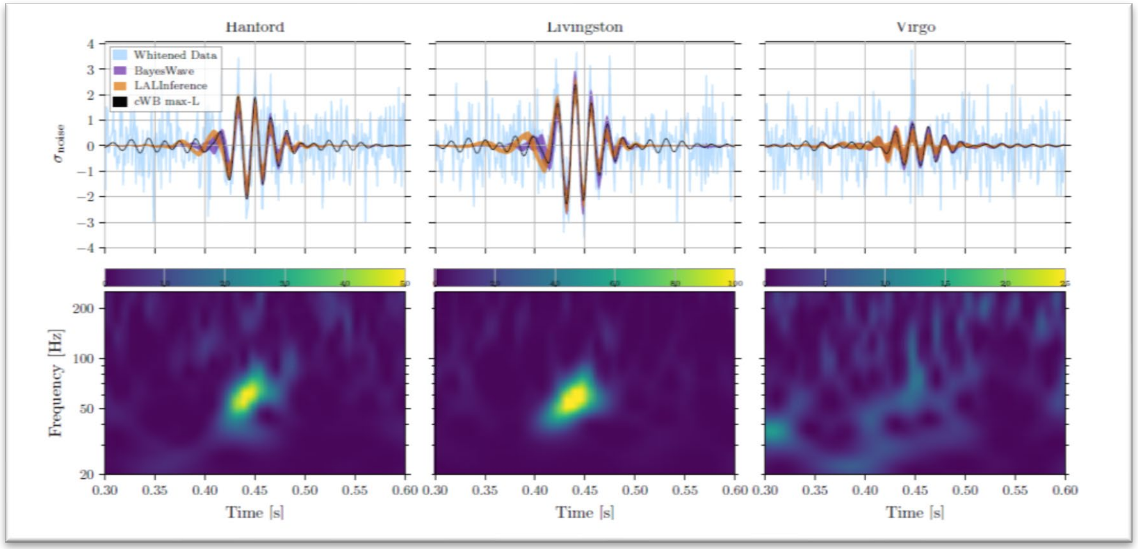
Masses



GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$







- Network SNR about 14-15
- BBH z=0.8 with unusually high component masses
- Mild evidence for spin-induced orbital precession
- **Primary in mass gap for pair-instability SN theory**
- Final: IMBH
- Formation channels?
  - Multiple stellar coalescence
  - Hierarchical merger of lower-mass black holes

- Short signal, difficult to analyze

Phys. Rev. Lett. 125, 101102 (2020)

Astrophys. J. Lett. 900, L13 (2020)

GW200105/GW200115

The Astrophysical Journal Letters, 915:L5 (24pp), 2021 July 1 https://doi.org/10.3847/2041-8213/ac082e
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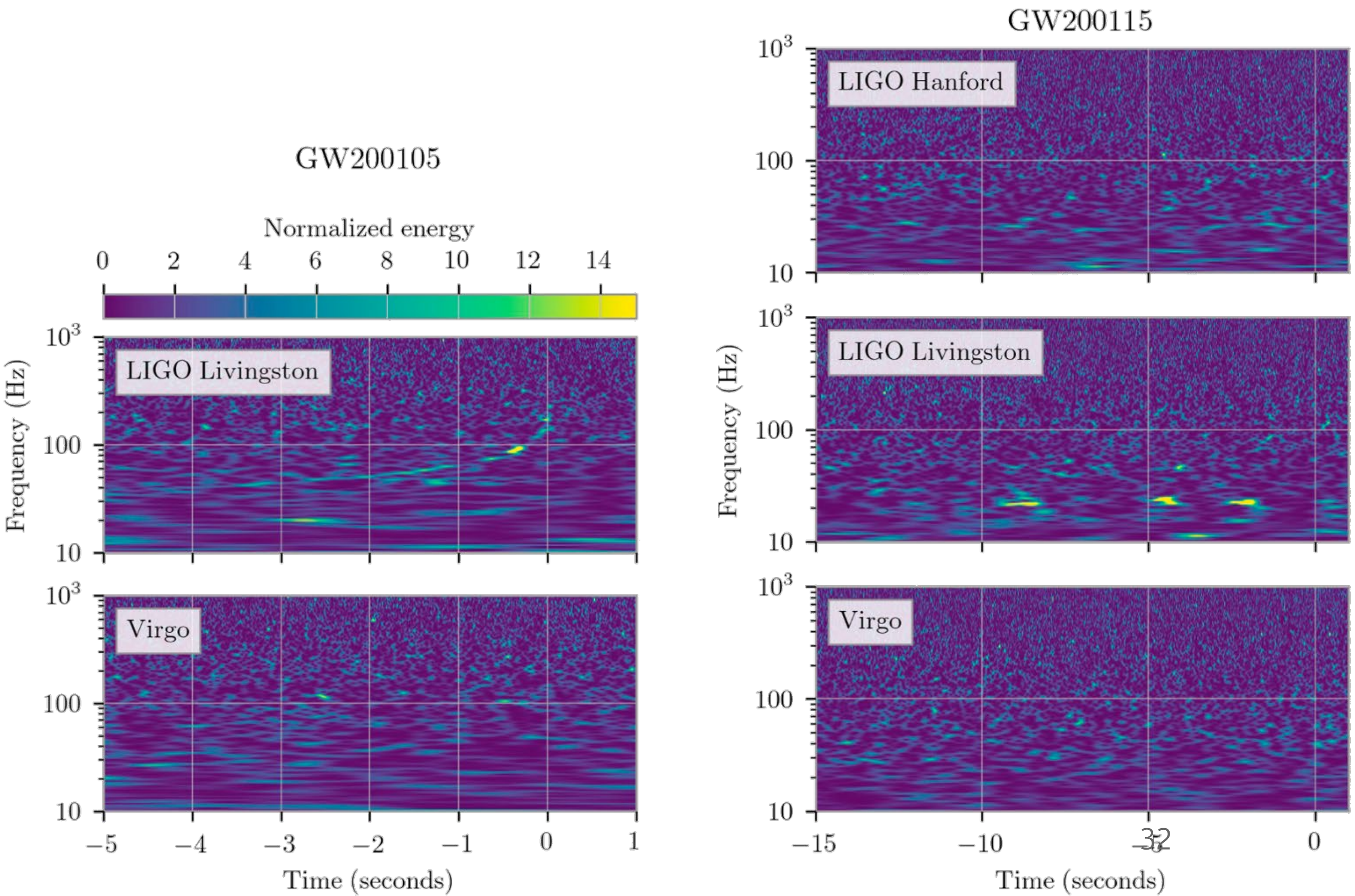
Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences

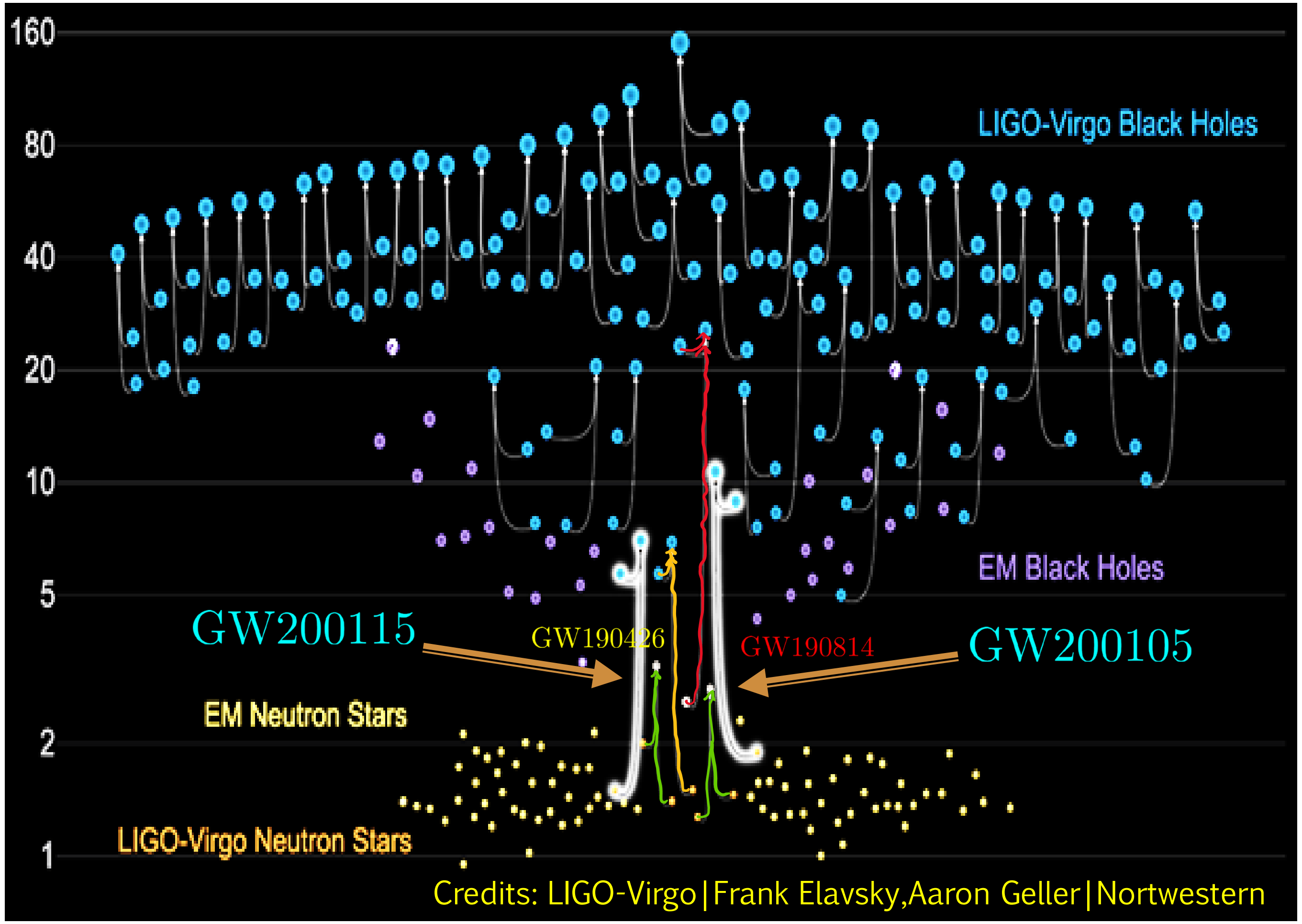
- GW200105 was observed by two detectors (LIGO Livingston & Virgo). The signal can be appreciated directly in the LIGO Livingston time-frequency map;
- GW200115 was observed by three detector LIGO-Virgo detector network. Note the low frequency features in LIGO Livingston: this is (non stationary/non Gaussian) noise.
- In both cases, Virgo SNR was not high enough for a detection claim
- Parameter estimation is a different issue: there all the observed data are used



The compact objects zoo

We know about compact objects both from GW and electromagnetic observations.

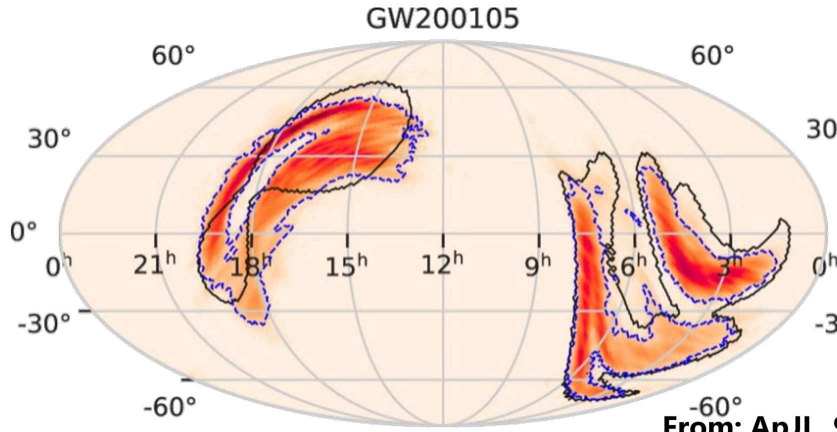
- **GW200105/GW200115** where not the first candidates for NSBH coalescences
- GW190426: in principle good parameters, but we have low confidence about the reality of this event
- GW190814: a real (and interesting) event. But the secondary mass is quite large for a neutron star ($2.50 M_\odot < m < 2.67 M_\odot$ at 90% confidence). Probably a BHBH. See: R. Abbott *et al* 2020 *ApJL* **896** L44



Credits: LIGO-Virgo|Frank Elavsky,Aaron Geller|Nortwestern

Localization and follow-up

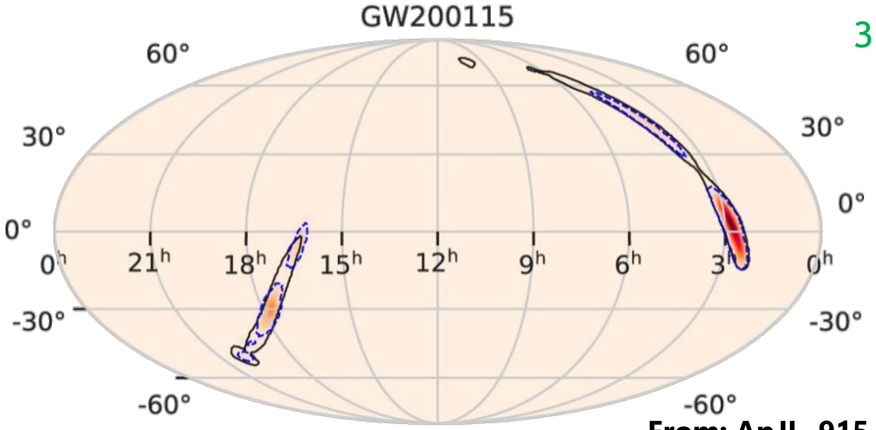
- Sky localization:
  $7700\ \mathrm{deg}^2 \rightarrow 6000\ \mathrm{deg}^2$
- $170\ \mathrm{Mpc} < D_L < 390\ \mathrm{Mpc}$
- Several follow-ups:
  no counterparts



2 detectors

From: ApJL, 915, L5 (2021)

- Sky localization:
  $900\ \mathrm{deg}^2 \rightarrow 600\ \mathrm{deg}^2$
- $200\ \mathrm{Mpc} < D_L < 450\ \mathrm{Mpc}$
- Several follow-ups:
  no counterparts



3 detectors

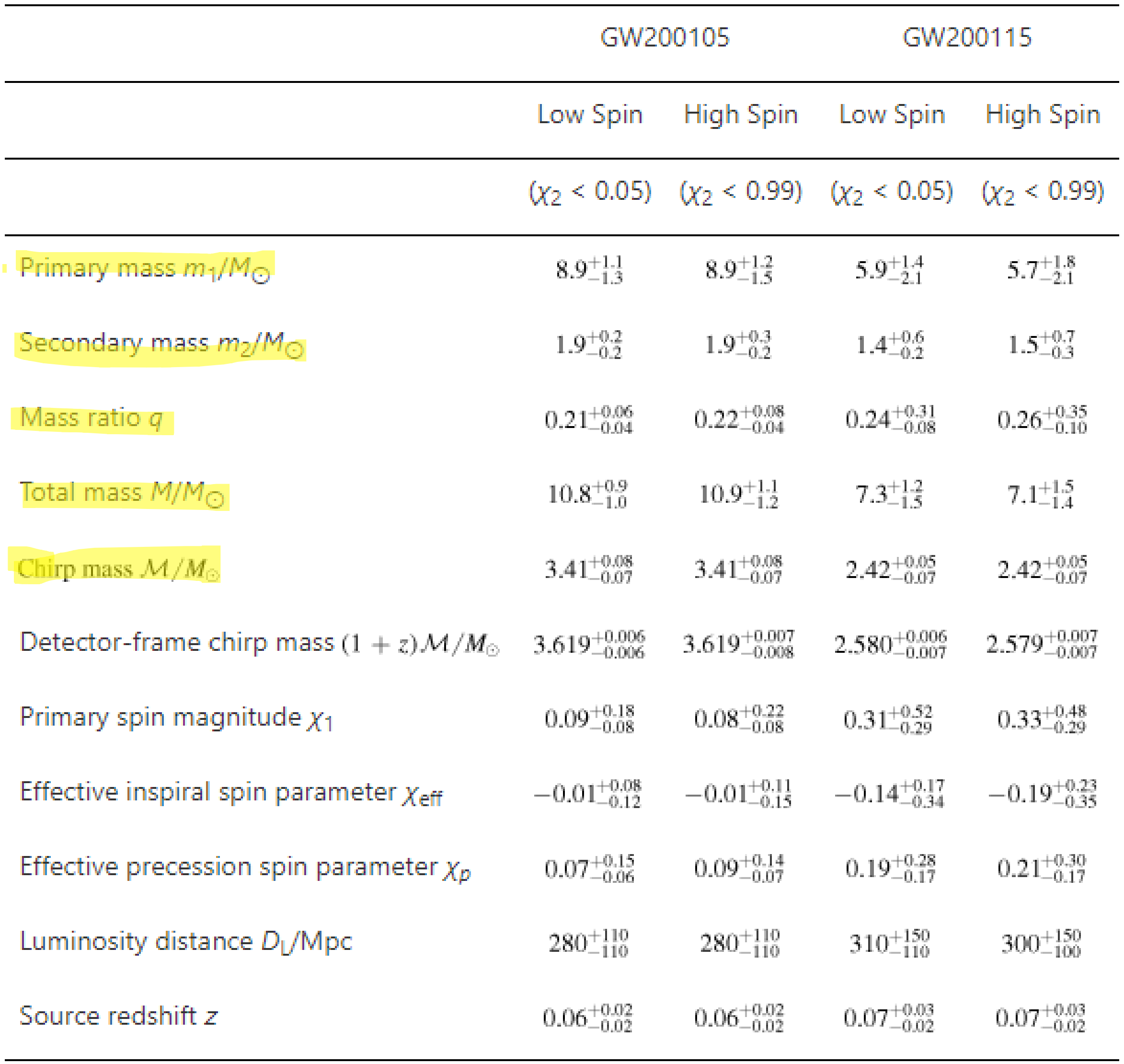
From: ApJL, 915, L5 (2021)

Thick solid contours: 90% credible regions from the low-latency sky localization algorithm

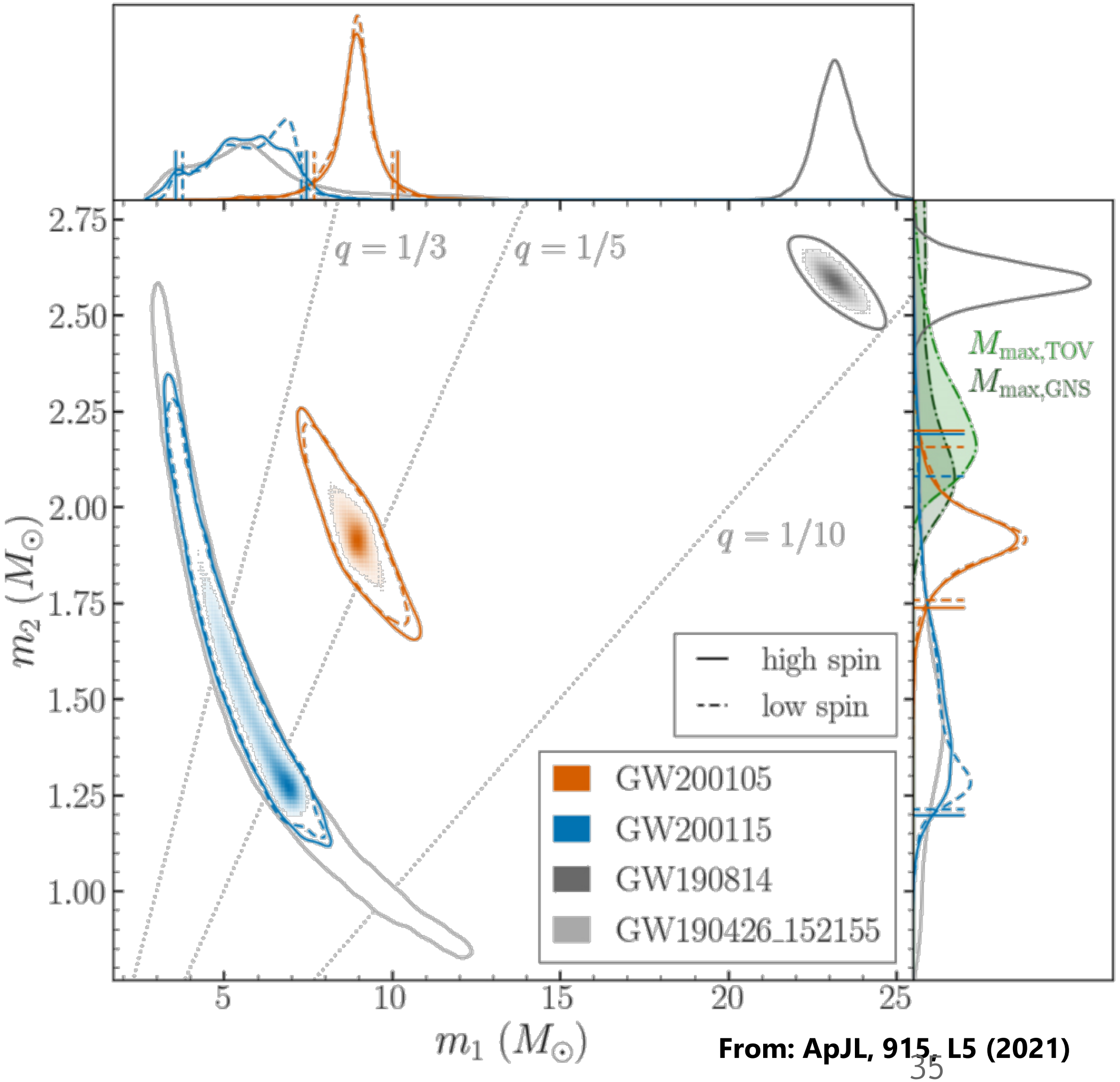
Shaded patch: preferred high-spin analysis, dotted contours are 90% credible regions

Singer LP and Price L 2016 *PRD* **93** 024013 , Speagle J. S. 2020 *MNRAS* **493** 3132, Lange J., O'Shaughnessy R. and Rizzo M. 2018 arXiv:1805.10457, Veitch J., Raymond V., Farr B. *et al* 2015 *PRD* **91** 042003

Masses



	GW200105		GW200115	
	Low Spin	High Spin	Low Spin	High Spin
	(χ_2 < 0.05)	(χ_2 < 0.99)	(χ_2 < 0.05)	(χ_2 < 0.99)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
Mass ratio q	$0.21^{+0.06}_{-0.04}$	$0.22^{+0.08}_{-0.04}$	$0.24^{+0.31}_{-0.08}$	$0.26^{+0.35}_{-0.10}$
Total mass $M/M_\odot$	$10.8^{+0.9}_{-1.0}$	$10.9^{+1.1}_{-1.2}$	$7.3^{+1.2}_{-1.5}$	$7.1^{+1.5}_{-1.4}$
Chirp mass $\mathcal{M}/M_\odot$	$3.41^{+0.08}_{-0.07}$	$3.41^{+0.08}_{-0.07}$	$2.42^{+0.05}_{-0.07}$	$2.42^{+0.05}_{-0.07}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$3.619^{+0.006}_{-0.006}$	$3.619^{+0.007}_{-0.008}$	$2.580^{+0.006}_{-0.007}$	$2.579^{+0.007}_{-0.007}$
Primary spin magnitude χ_1	$0.09^{+0.18}_{-0.08}$	$0.08^{+0.22}_{-0.08}$	$0.31^{+0.52}_{-0.29}$	$0.33^{+0.48}_{-0.29}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.01^{+0.08}_{-0.12}$	$-0.01^{+0.11}_{-0.15}$	$-0.14^{+0.17}_{-0.34}$	$-0.19^{+0.23}_{-0.35}$
Effective precession spin parameter χ_p	$0.07^{+0.15}_{-0.06}$	$0.09^{+0.14}_{-0.07}$	$0.19^{+0.28}_{-0.17}$	$0.21^{+0.30}_{-0.17}$
Luminosity distance D_L/Mpc	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$

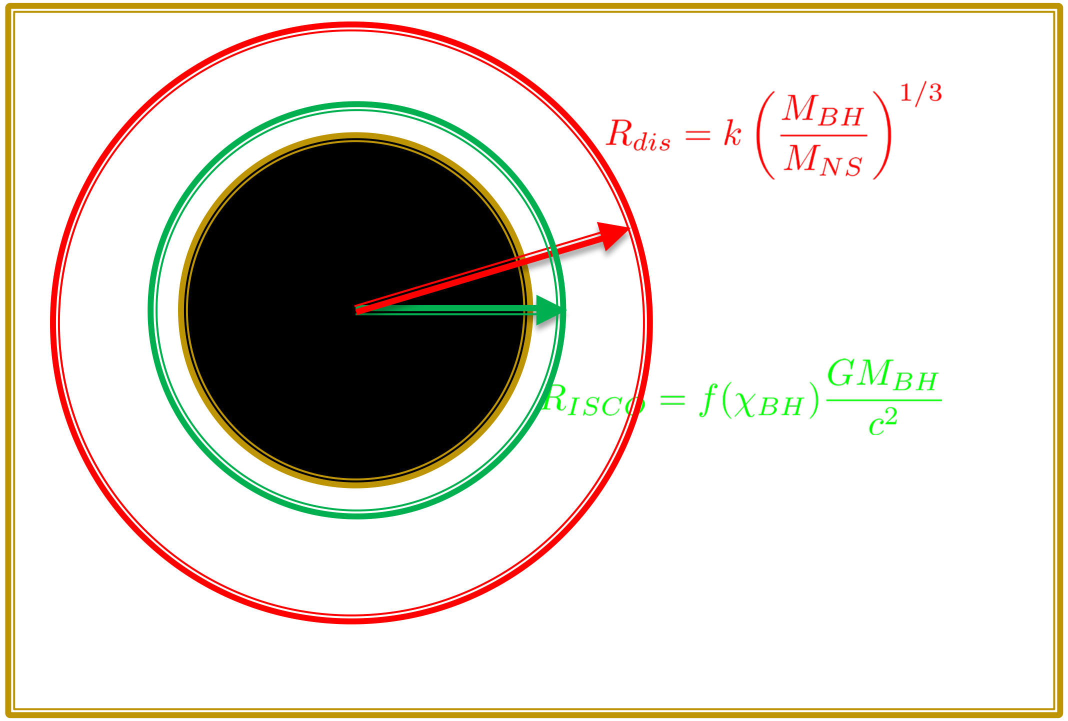


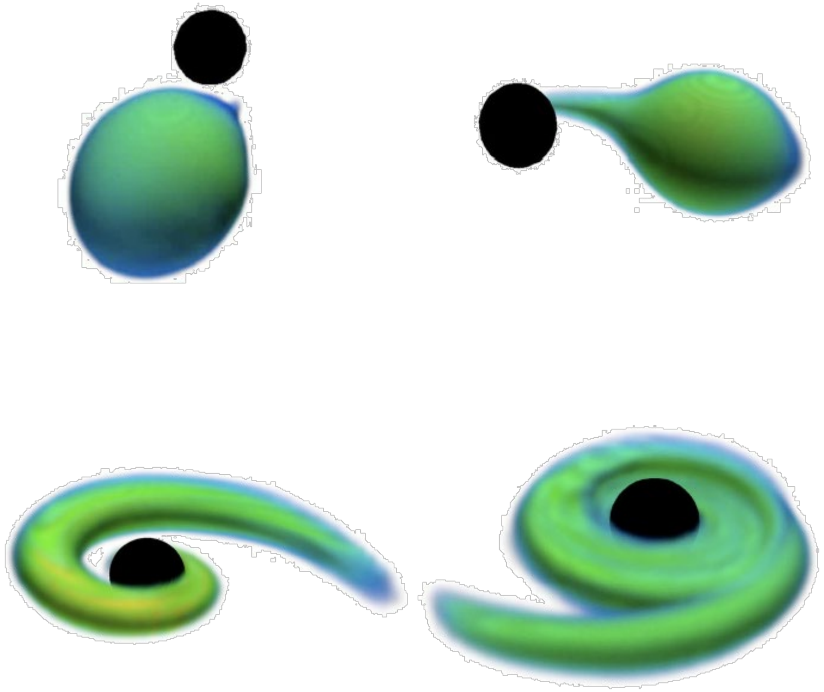
From: ApJL, 915, L5 (2021)

Direct evidence of NS

- The deformability parameter is very small when $M_{BH} \gg M_{NS}$

$$\tilde{\Lambda} = \frac{32}{39} \frac{M_{NS}^4 (M_{NS} + 12 M_{BH})}{(M_{NS} + 12 M_{BH})^5} \left(\frac{R_{NS} c^2}{G M_{NS}} \right)^5 k_2$$



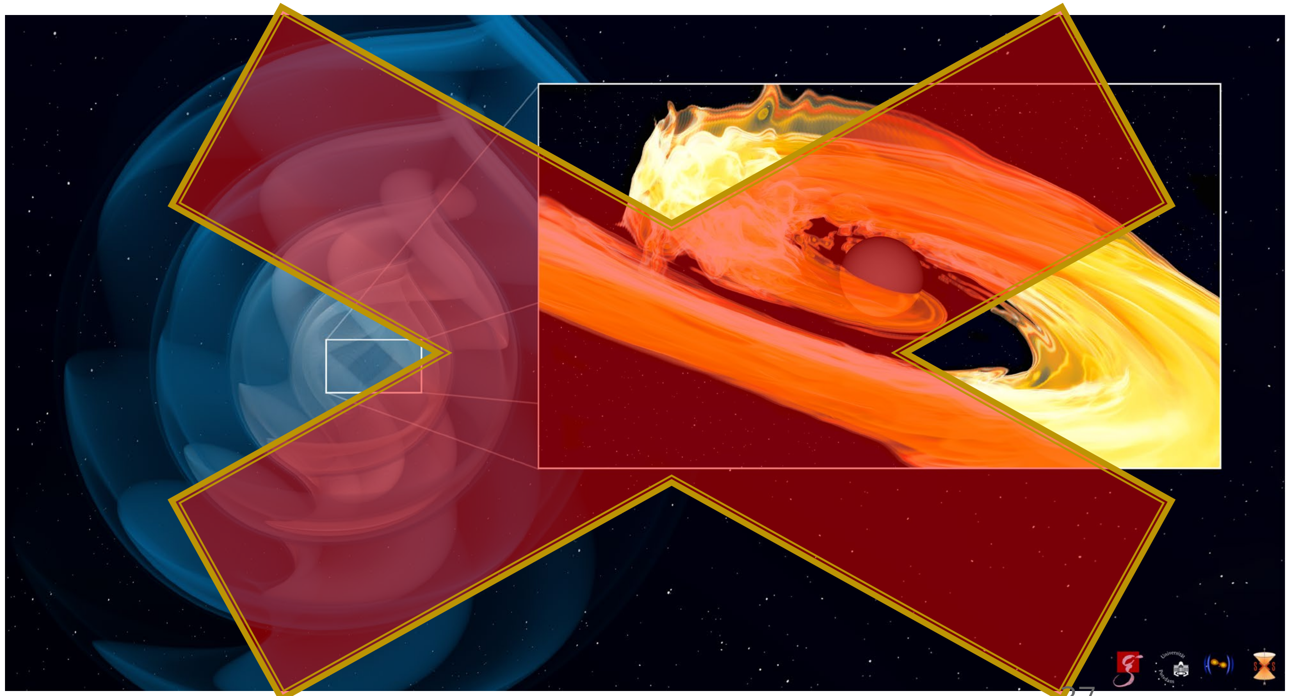


Foucart F (2020) Front. Astron. Space Sci. 7:46. doi: 10.3389/fspas.2020.00046

Why no electromagnetic counterpart?

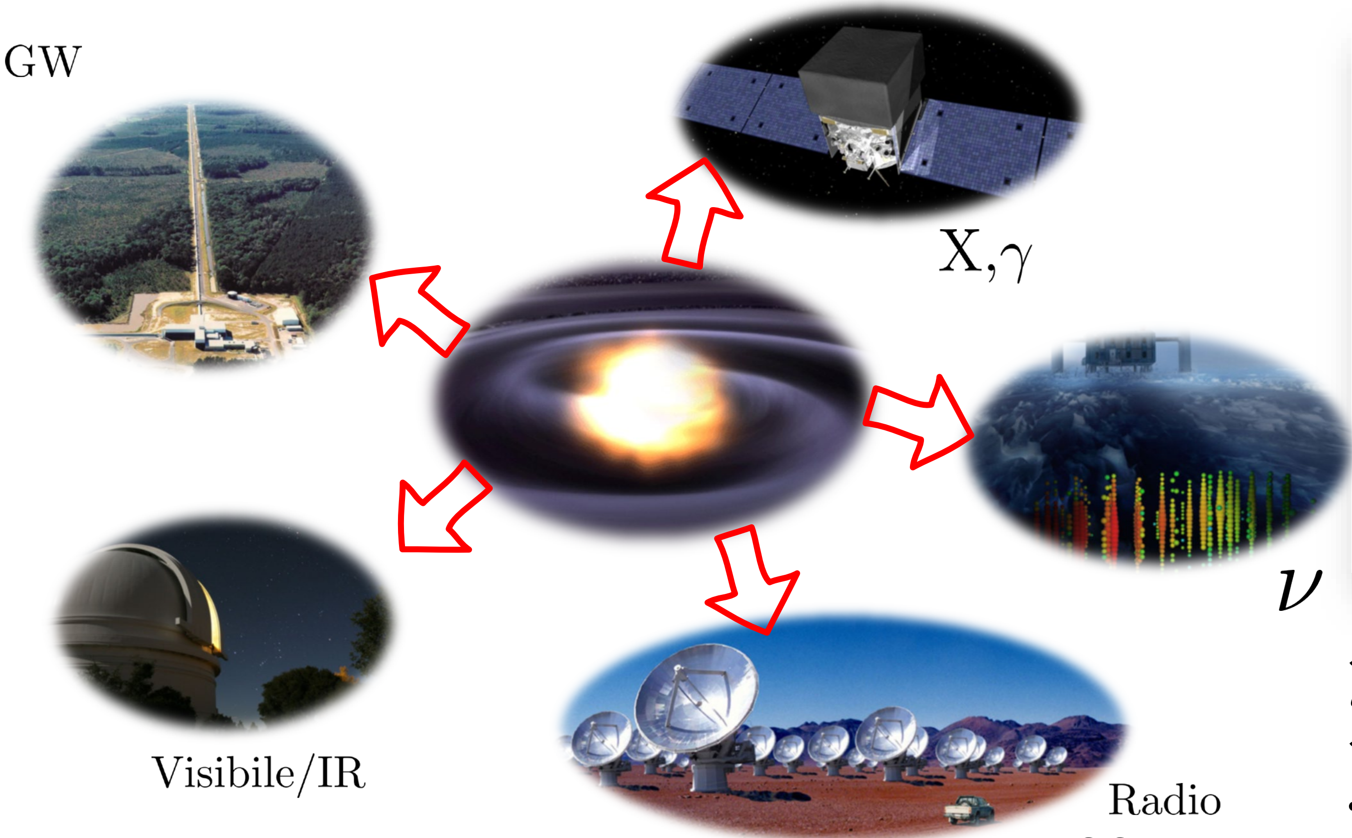
- Several observations, but no convincing electromagnetic counterparts. This is not surprising, for several reasons:
    - With the observed (too large) mass asymmetries, no tidal disruption is expected.
    - Note that anti-aligned spins suppress disruption
    - Events are far from us
    - There is a large uncertainty in localization, which reduces the chances of a positive follow up

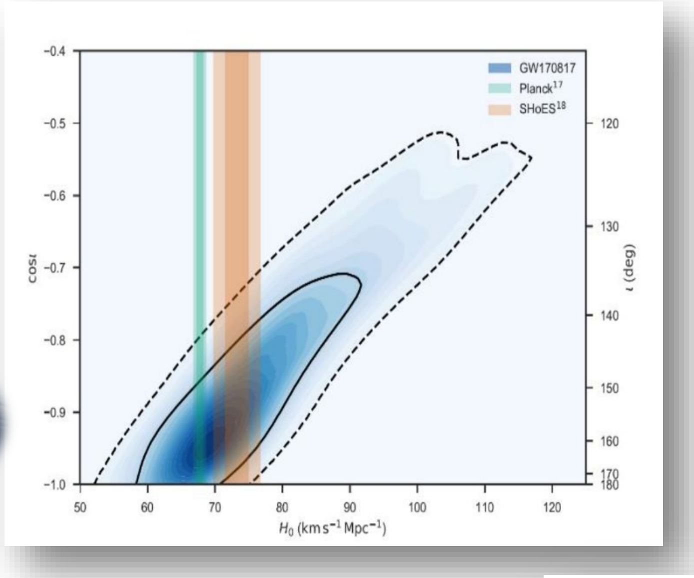
- Some improvement is expected with a better sensitivity
    - Event rate will increase, so it will be possible to better explore the large space of parameters for this kind of events
    - Sky localization (and parameter estimation) could improve for louder events



[Image credit: S.V.Chaurasia (Stockholm University), T. Dietrich (Potsdam University and Max Planck Institute for Gravitational Physics), N. Fischer, S. Ossokine, H. Pfeiffer (Max Planck Institute for Gravitational Physics), T. Vu.]

Multimessenger





Independent method for Hubble parameter determination: GW are a new cosmic distance marker

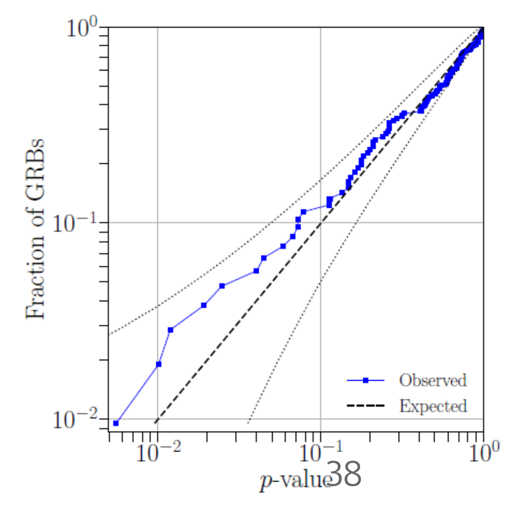
Abbott et al. 2017, Nature, 551, 85A

- Most direct way: when we have an optical counterpart
- Alternatively: by localizing the host galaxy
- And/or: statistically, on a large sample of events

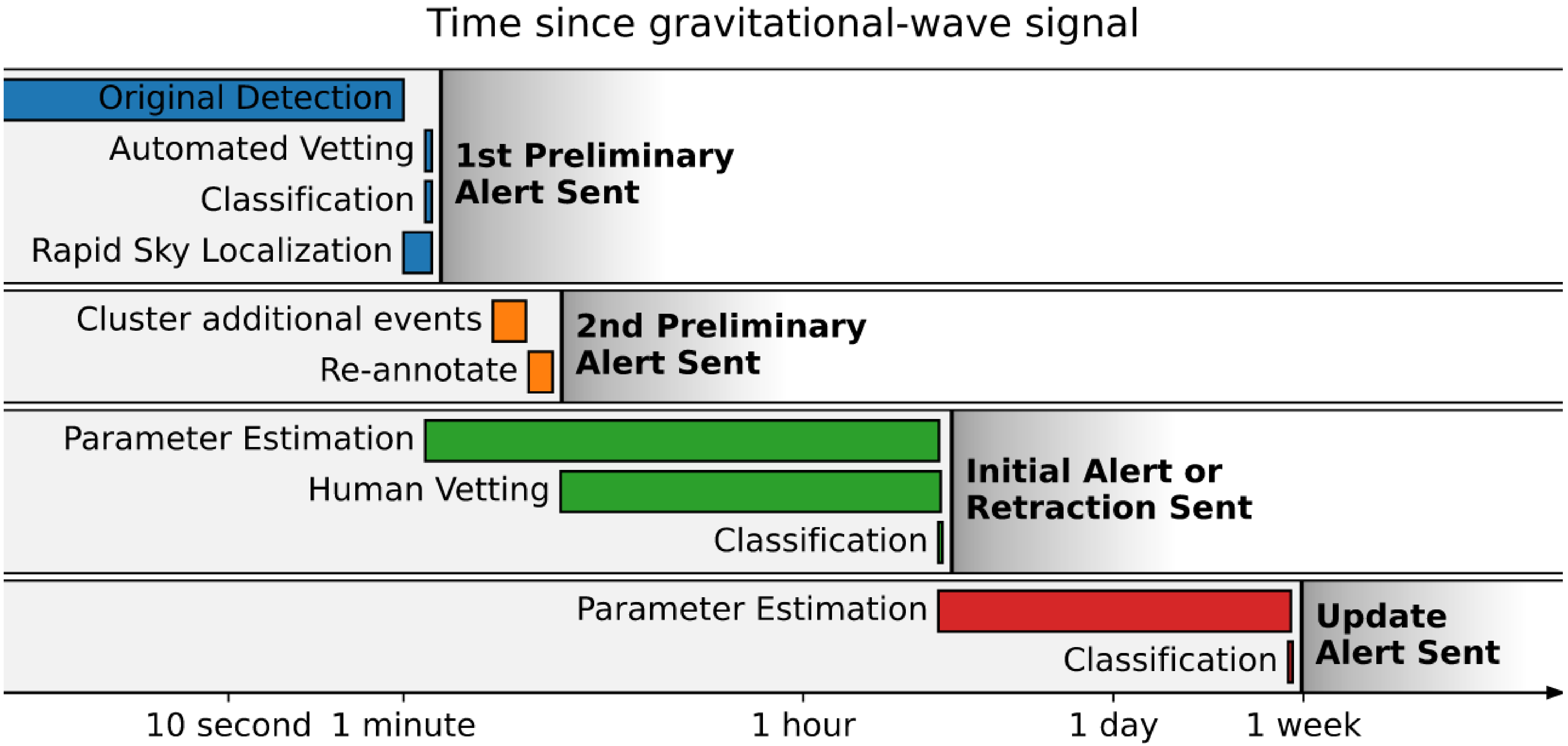
No solid electromagnetic counterparts found in O3
Several attempts, not confirmed
We are looking far, and GW are not beamed.
What we could do better?
GW side ➔ improve localization
em side ➔ improve sensitivity

Search on O3a data set, using detection from Fermi & Swift satellites.

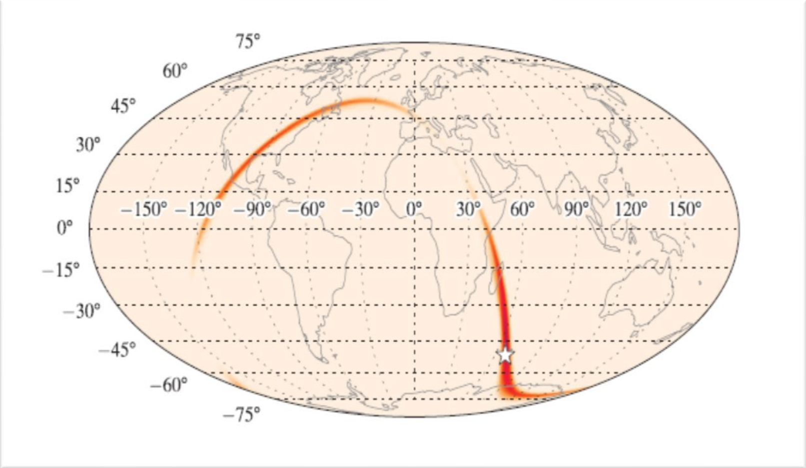
- No significant evidence for gravitational-wave signals associated with the followed-up GRB
- Lower bounds on the rate of short gamma-ray bursts as a function of redshift for $z \leq 1$

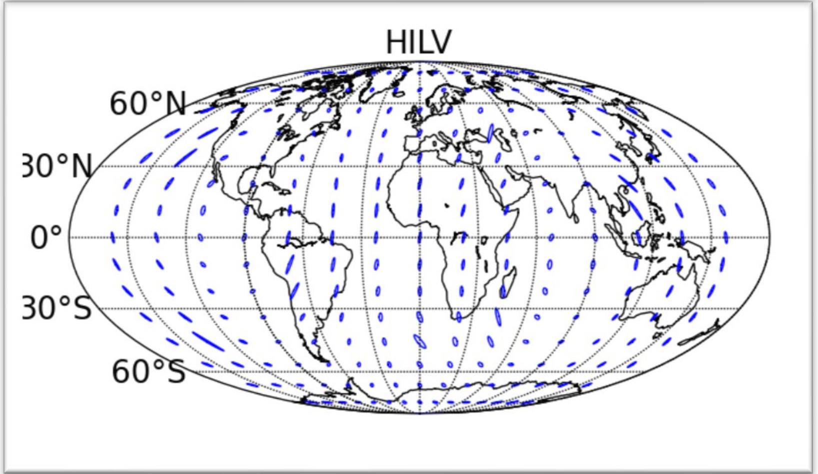


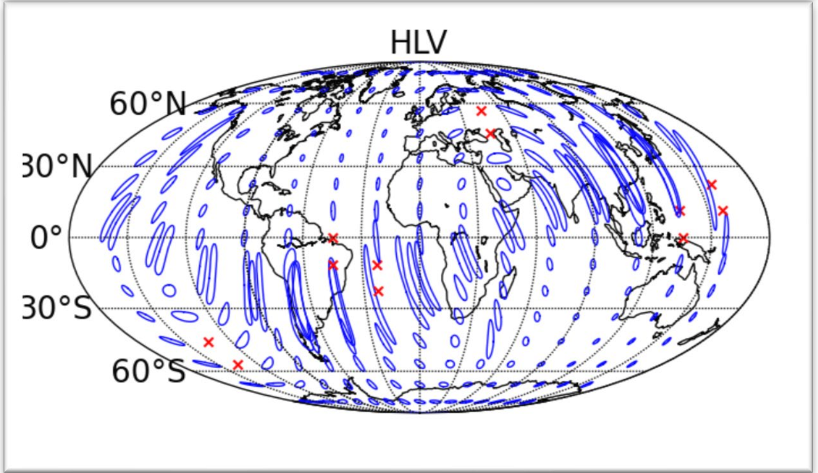
Alert timeline in O3
(see https://emfollow.docs.ligo.org/userguide/index.html)



Localization



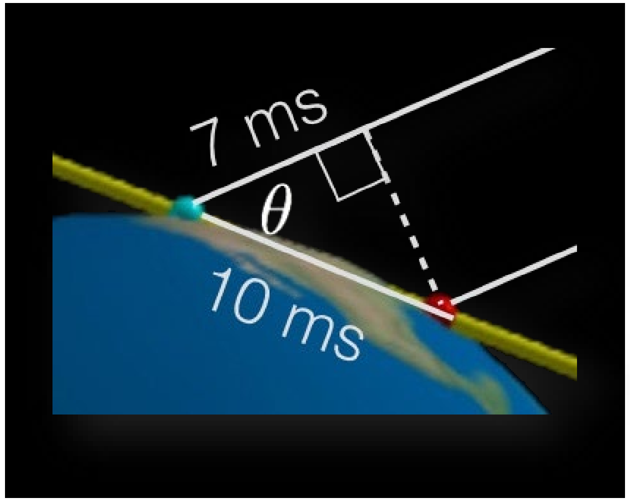


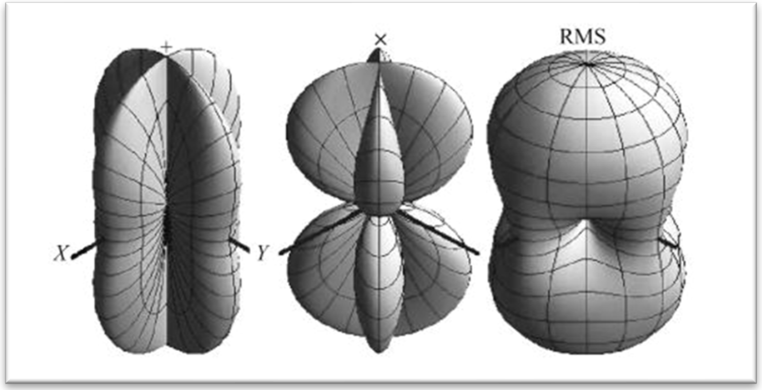


- Localization is roughly proportional to the timing accuracy $\Delta\tau$,

$$\Delta\tau = \frac{1}{2\pi\,\mathrm{SNR}\,\Delta f}$$

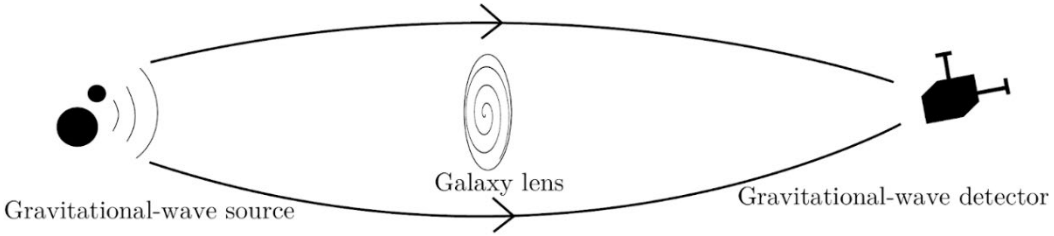
- Phase and amplitude consistency are taken into account also.



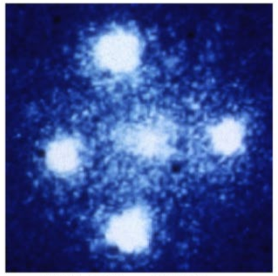


Gravitational lensing of GW

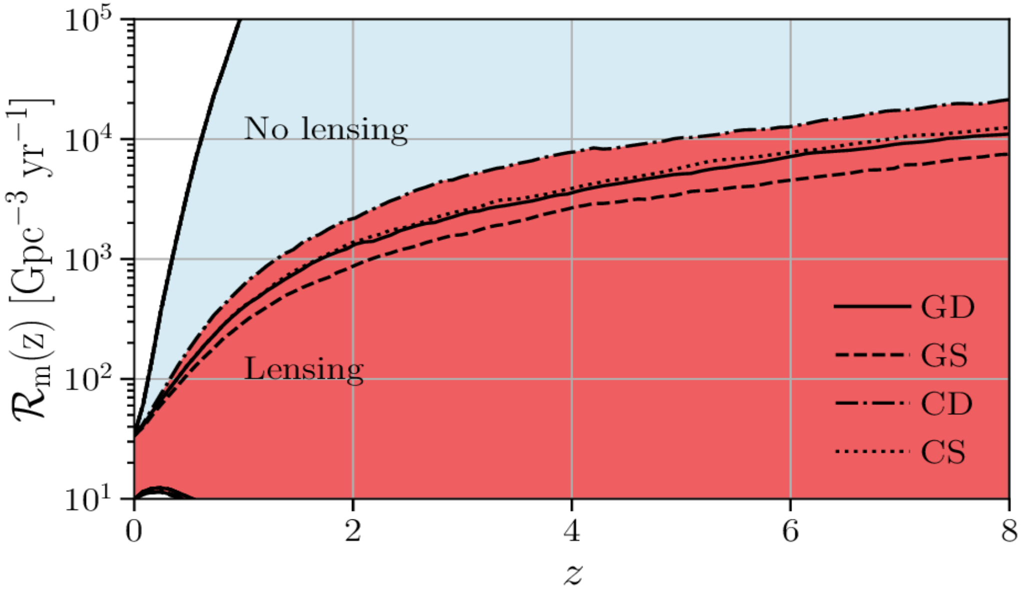
Astrophys. J. **923**, 14 (2021)




ESA/Hubble & NASA


NASA, ESA, and STScI


NASA, ESA, Hubble SM4 ERO Team, ST-ECF



Analogous to gravitational lensing of light GWs got:

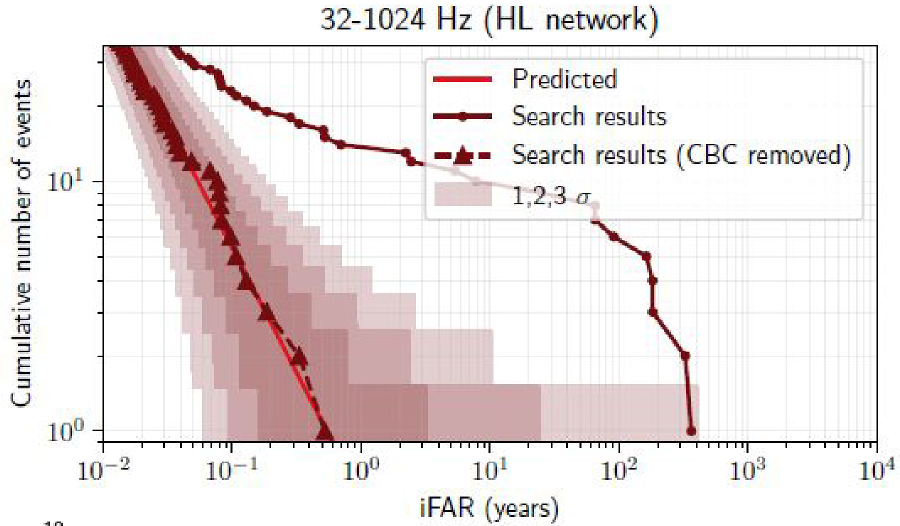
- Magnification
- Multiple “images”
- Frequency dependent deformations

Potentially:

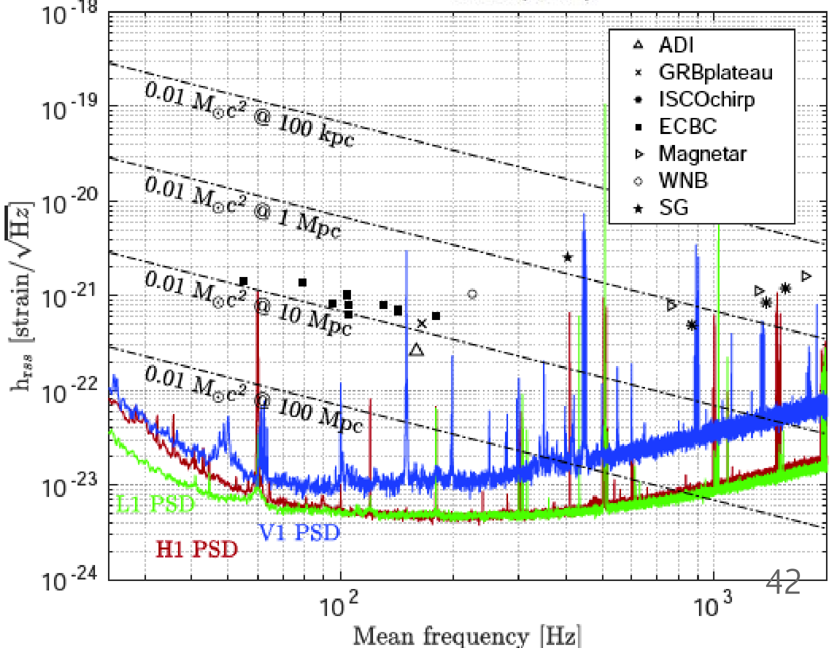
- Test of fundamental physics
- Localization of merging BH
- Precision cosmology
- Microlens population studies

GW transients un-modeled searches

- All-sky search for short GWs bursts. Astrophysics sources could include: BBH, CCSNe, cosmic strings, pulsar glitches (*arxiv:2107.03701*):
  - all sky unmodeled search for GW transients < 1s
  - no new candidates found apart from CBC sources
  - set current upper limit (about one order of magnitude better than the previous O2 limit over most of the frequency bandwidth)



- All-sky search for long GW bursts. Astrophysics sources could include fallback accretion, accretion disk instabilities, newborn neutron stars from BNS merger or core-collapse supernovae, eccentric compact binary coalescences (*arxiv:2107.13796*):
  - all sky un-modeled search for GW transients 2-500 s
  - no new candidates found
  - amplitude sensitivity improved by a factor of 1.8 wrt the analysis from O2

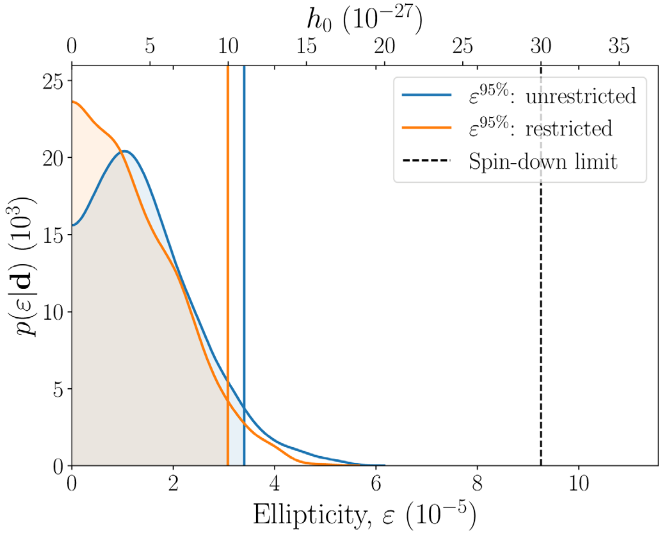


- IMBH search & GRB search
  - Search for intermediate-mass black hole binaries in the third observing run of Advanced LIGO and Advanced Virgo
  - Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift During the LIGO-Virgo Run O3b
  - In preparation: magnetar bursts, FRB triggered search, eccentric BBH

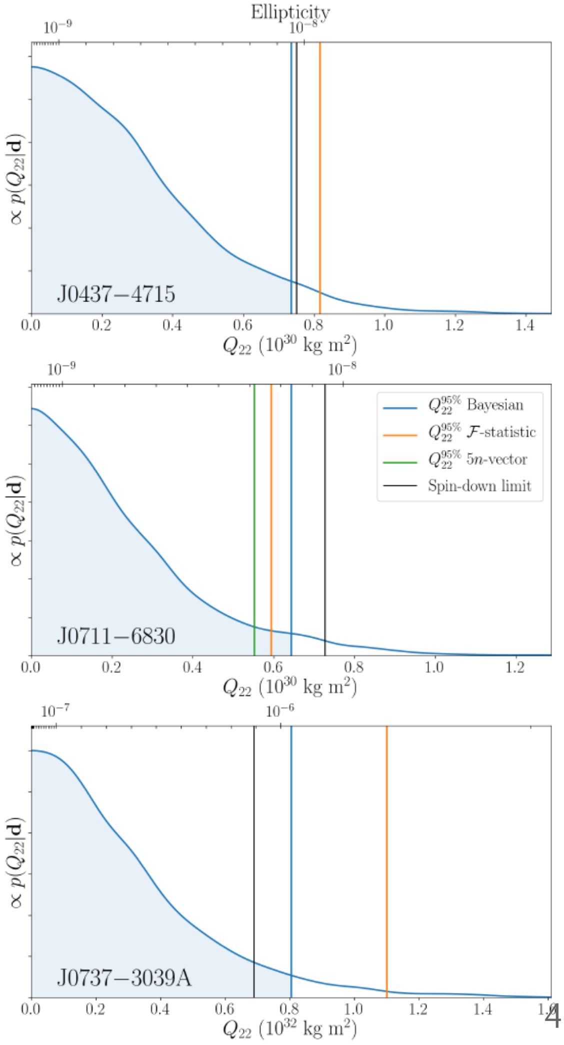
CW searches

- Weak and persistent signal.
  - Targeted (particular source)
  - All sky (unknown sources)
- Not really monocromatic
  - Modulations
  - Spin down, environment effects, glitches

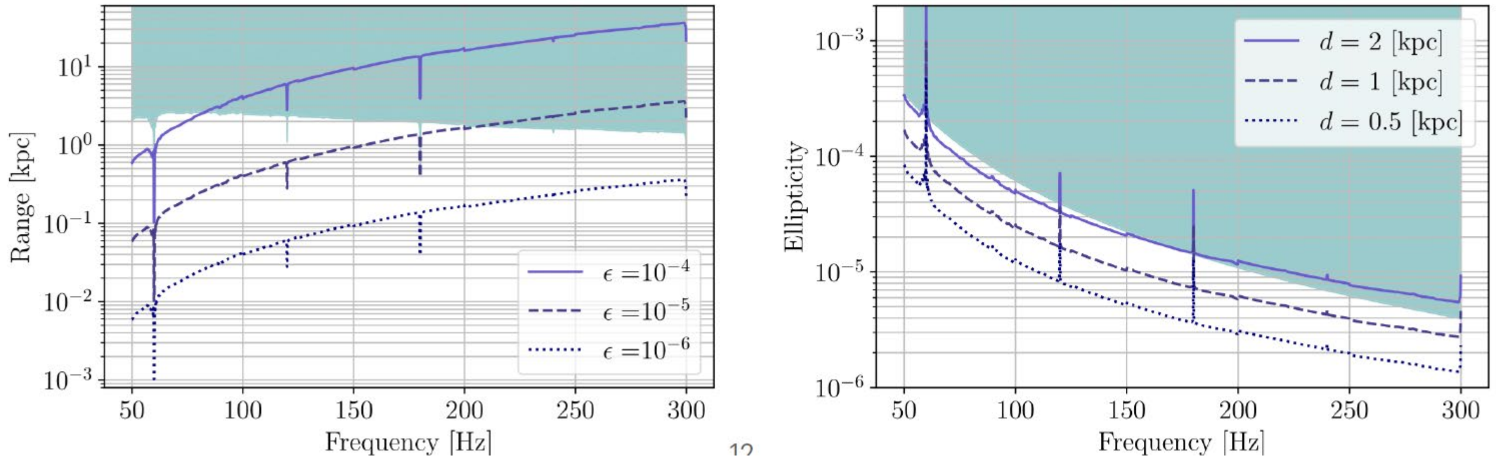
J0537-6910
Abbott et al. arXiv:2012.12926



Beating spindown limit
Abbott et al. ApJL 902 L21



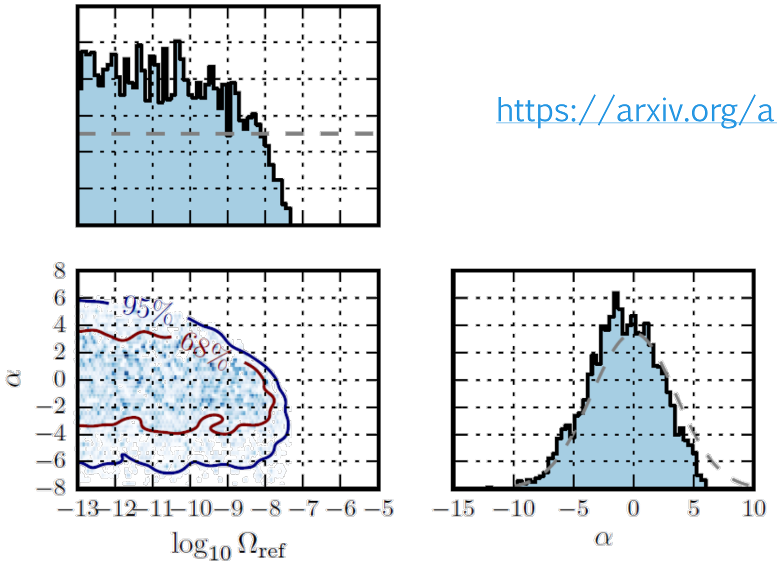
All-sky search
Abbott et al. arXiv:2012.12926



Stochastic background searches

Upper Limits on the Isotropic Gravitational-Wave Background from Advanced LIGO's and Advanced Virgo's Third Observing Run

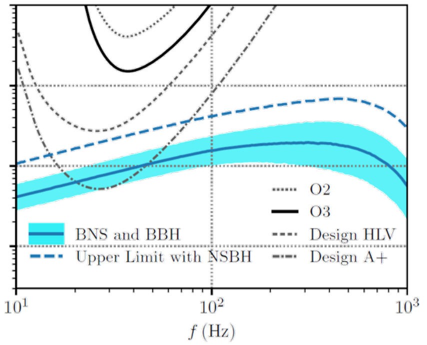
https://arxiv.org/abs/2101.12130



$$\Omega_{\mathrm{GW}}(f) = \Omega_{\mathrm{ref}}\left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha}$$

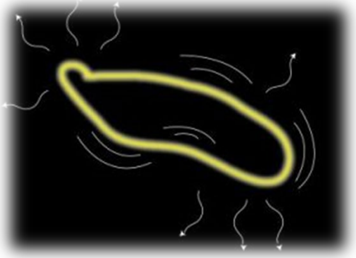
	Uniform prior			Log-uniform prior		
α	O3	O2 [43]	Improvement	O3	O2 [43]	Improvement
0	1.7×10^{-8}	6.0×10^{-8}	3.6	5.8×10^{-9}	3.5×10^{-8}	6.0
2/3	1.2×10^{-8}	4.8×10^{-8}	4.0	3.4×10^{-9}	3.0×10^{-8}	8.8
3	1.3×10^{-9}	7.9×10^{-9}	5.9	3.9×10^{-10}	5.1×10^{-9}	13.1
Marg.	2.7×10^{-8}	1.1×10^{-7}	4.1	6.6×10^{-9}	3.4×10^{-8}	5.1

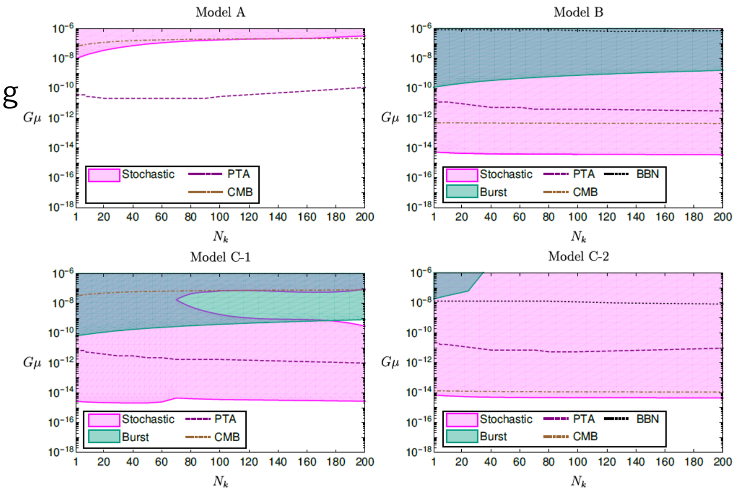
Polarization	O3	O2 [43]	Improvement
Tensor	6.4×10^{-9}	3.2×10^{-8}	5.0
Vector	7.9×10^{-9}	2.9×10^{-8}	3.7
Scalar	2.1×10^{-8}	6.1×10^{-8}	2.9

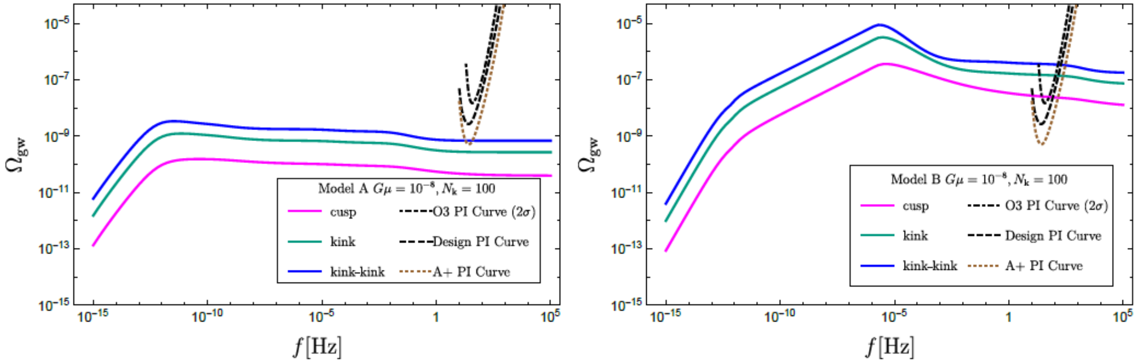


Constraints on cosmic strings using data from the third Advanced LIGO–Virgo observing run https://arxiv.org/abs/2101.12248

- Joint (and complementary) Stochastic-Burst search
- Put constraints on cosmic string models



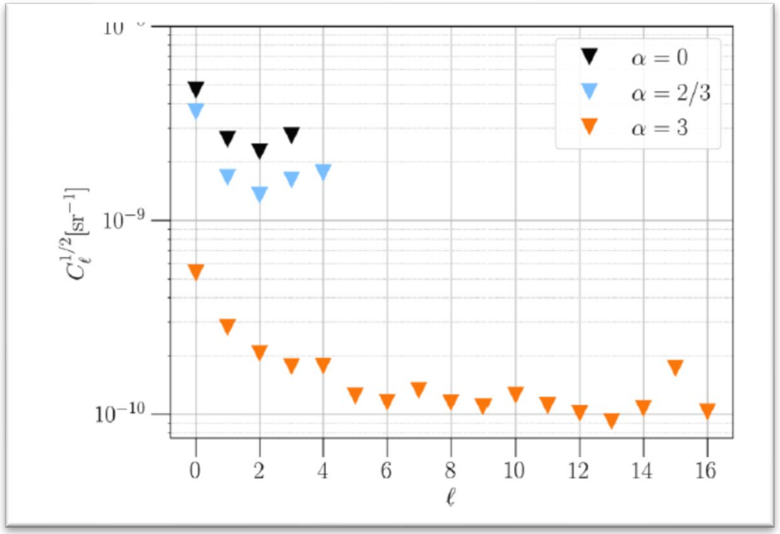


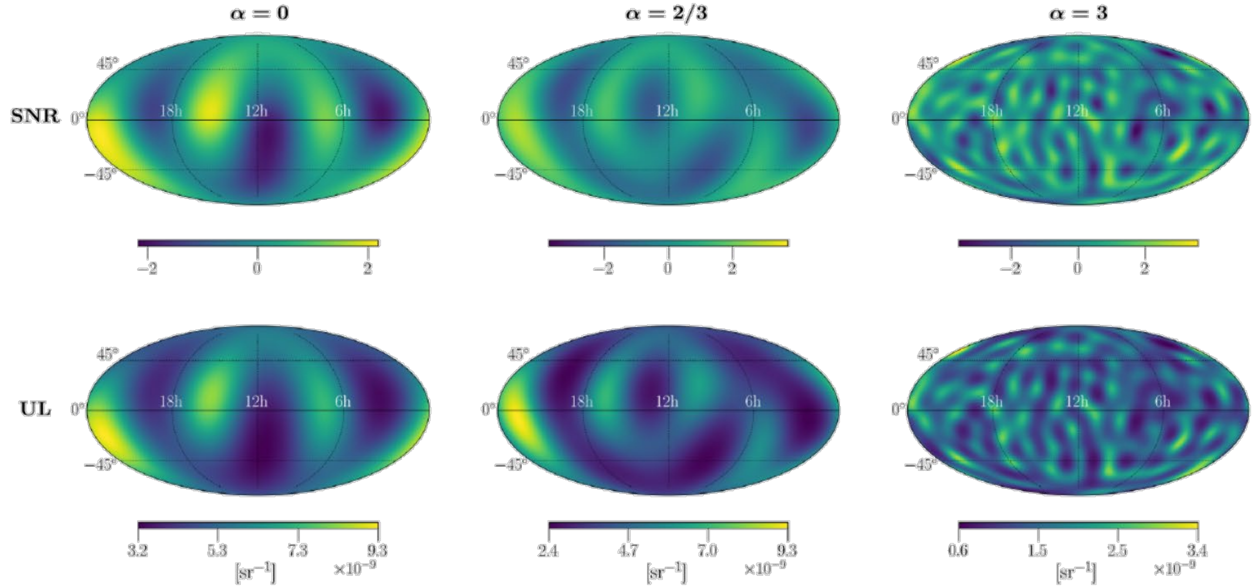


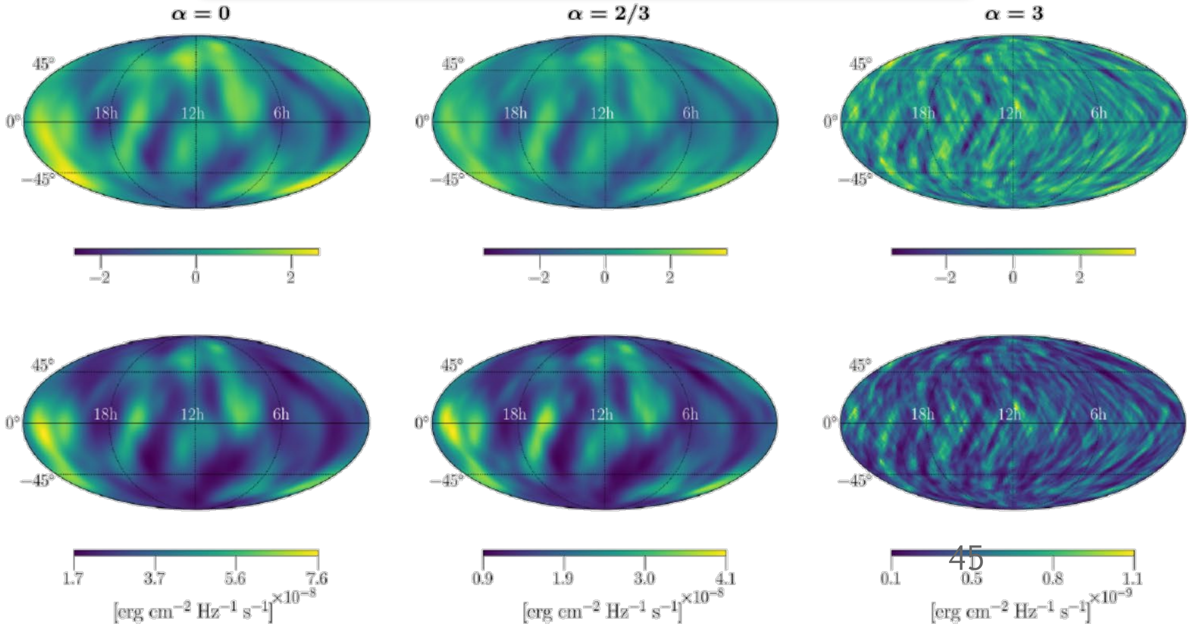
Stochastic background searches (Phys. Rev. D **104**, 022005)

It is also possible to look at anisotropies

- The single detector is not particularly directional, but the network is;
- At the moment, no evidence for a SBGW
- Continuously improving the upper limit for direction-dependent GW luminosity



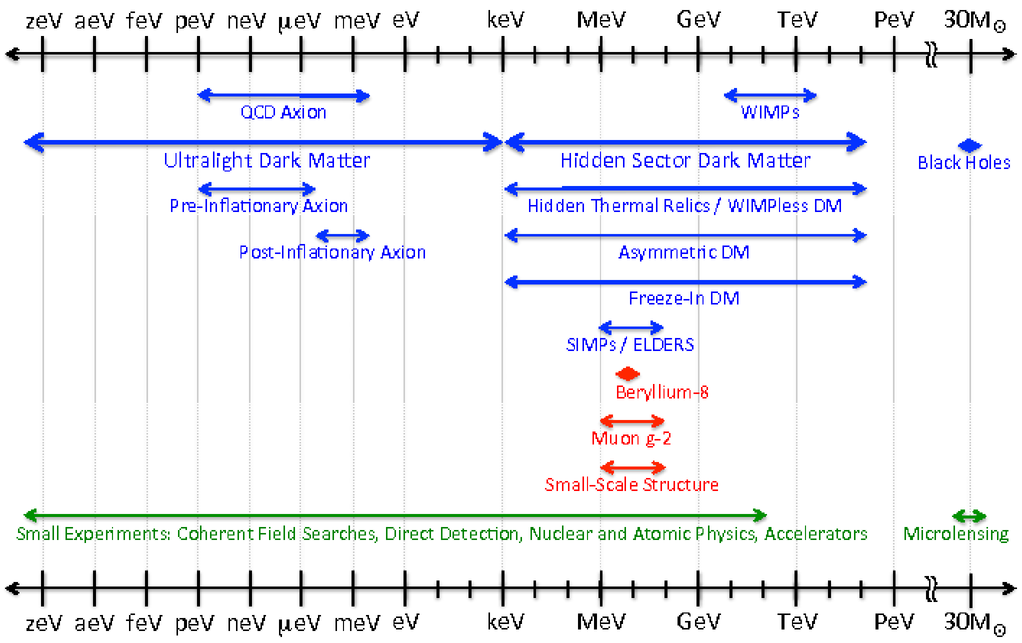




Gravitational waves and dark matter

- Evidences: CMB power spectrum, cluster & galactic rotation curves, gravitational lensing
- Large span for DM candidate masses: from ultralight bosons ($\sim 10^{-22}$eV) to BH ($\sim 1 - 100\ M_{\odot}$).
- Gravitationally interacting, gravitational physics can help!
- GW sources can be affected by DM
  - By changes of their evolution by environmental effects
  - By changes of their nature and dynamics (when new interactions exist in the DM sector). They can be DM candidates by itself (SSM black holes)

Dark Sector Candidates, Anomalies, and Search Techniques



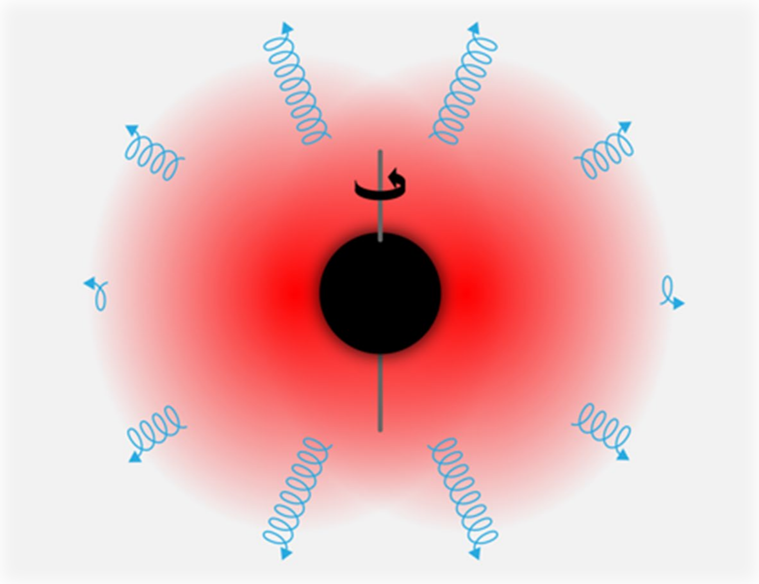
Reference: arXiv:1707.04591

DM candidates searchable with gravitational waves

- **Environmental effects on compact objects**
  - The **compact object structure** can be changed: accretion disk, spin down effects, formation of a DM core
  - The GW **production mechanism** can be changed
  - **Inpact on propagation** of generated GW and EM waves
  - ➙ ***Signature:*** *Unusual waveform*
- **Primordial black holes**
  - Microlensing data seems to exclude that ALL DM can be explained in this way.
  - Not completely uncontroversial, some assumptions can be weakened;
  - Could be responsible for a fraction of DM;
  - ➙ ***Signature:*** *Subsolar mass BH evidence*
- **Exotic objects**
  - GW190521 is compatible with a merger between two complex vector boson star, with $m_b \sim 8.7 \times 10^{-13}$ eV (head on collision)

  See Phys. Rev. Lett. **126**, 081101

- Superradiance effects
  - A Kerr BH can transfer efficiently its energy to a cloud of ultra-light bosons, (scalar or vector) when $\lambda_c \sim R_s$ (which means $10^{-21}eV < m_b < 10^{-11}eV$)
  - The cloud can emit a nearly-periodic, long duration GW signal potentially detectable by LIGO-Virgo-KAGRA if $10^{-13}eV < m_b < 10^{-11}eV$

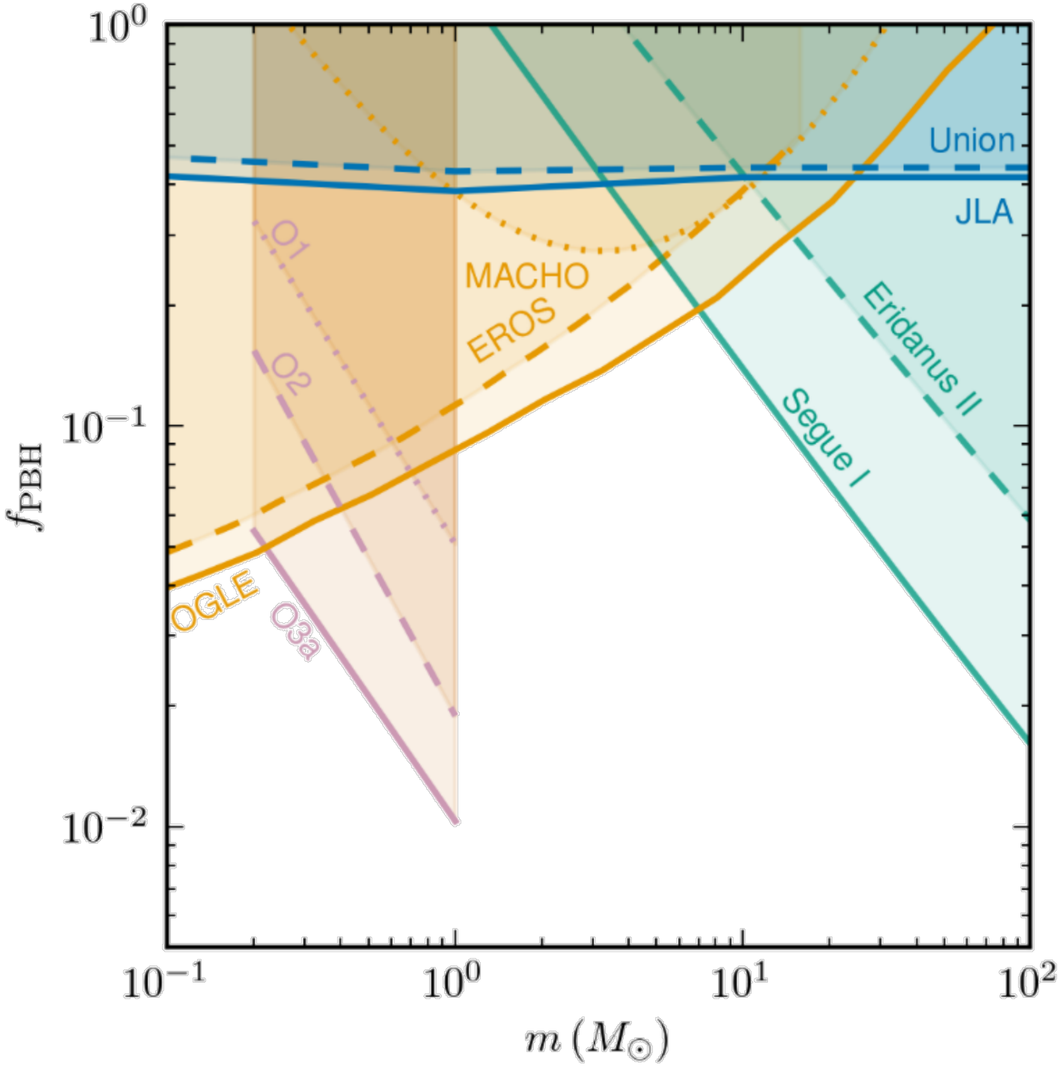


From: https://physics.aps.org/articles/v10/83

PRL 123, 171101 (2019)
PRD 101, 063020 (2020)
PRD 99, 084042 (2019)
PRD 98, 103017 (2018)

Subsolar mass BH search

- SSM BH cannot be produced by any astrophysical mechanism
- No candidate found
- Significative improvement of microlensing and SN lensing constraints
- Will improve in the future



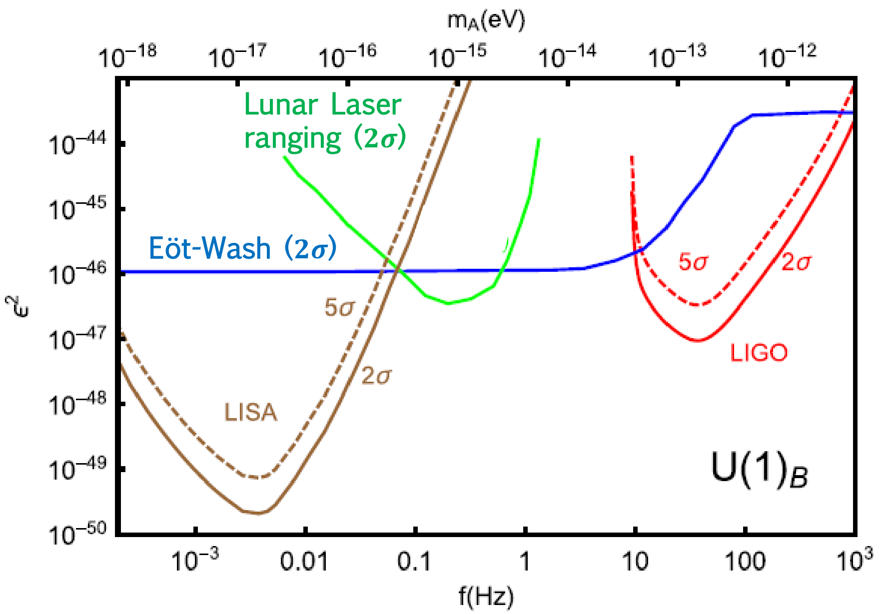
DM direct coupling

- DM can DIRECTLY (no GW) couple to the detector, in a way which depends on the candidate
  - Dilaton (fundamental constant modulation)
  - Axion (IF beam phase modulation)
  - dark photon (direct coupling to mirrors)
  - tensor,
  - ….
- Ultra-light DM: bosonic field with huge occupation numbers

➞ ***Signature:*** *Quasi-monochromatic (Maxwell-Boltzmann broadened) signal correlated between different detectors*

➞ *Frequency is determined by the mass*

➞ *Broadening contains information about DM distribution*

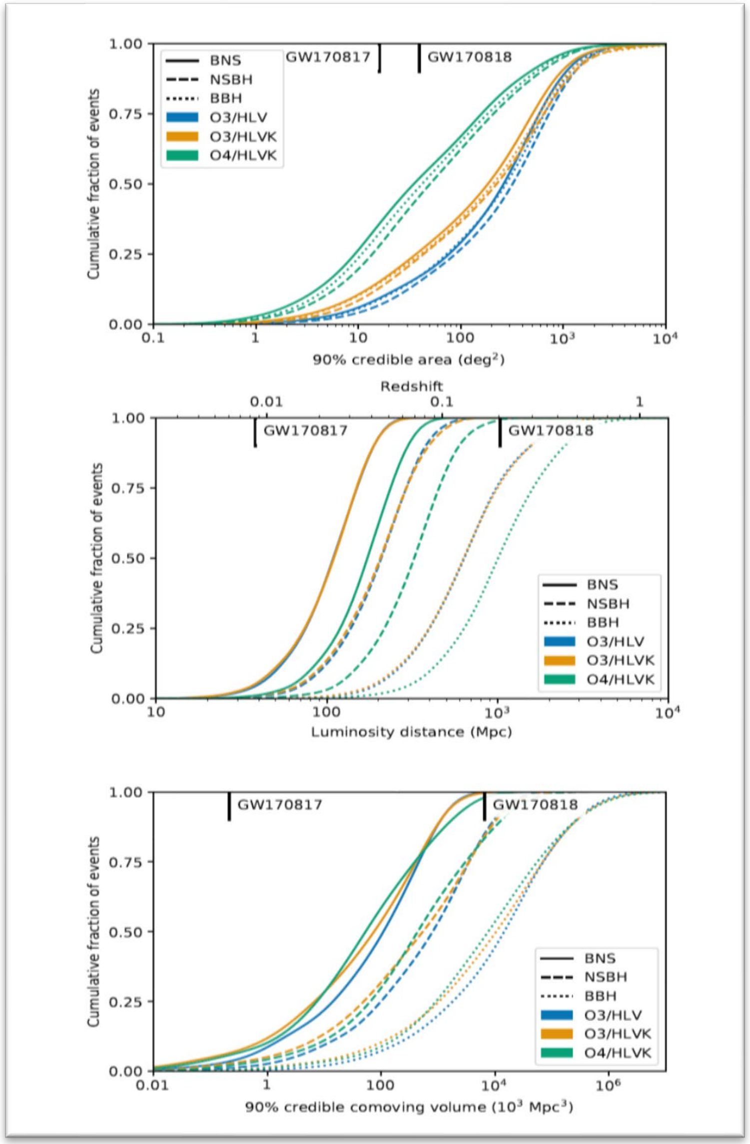


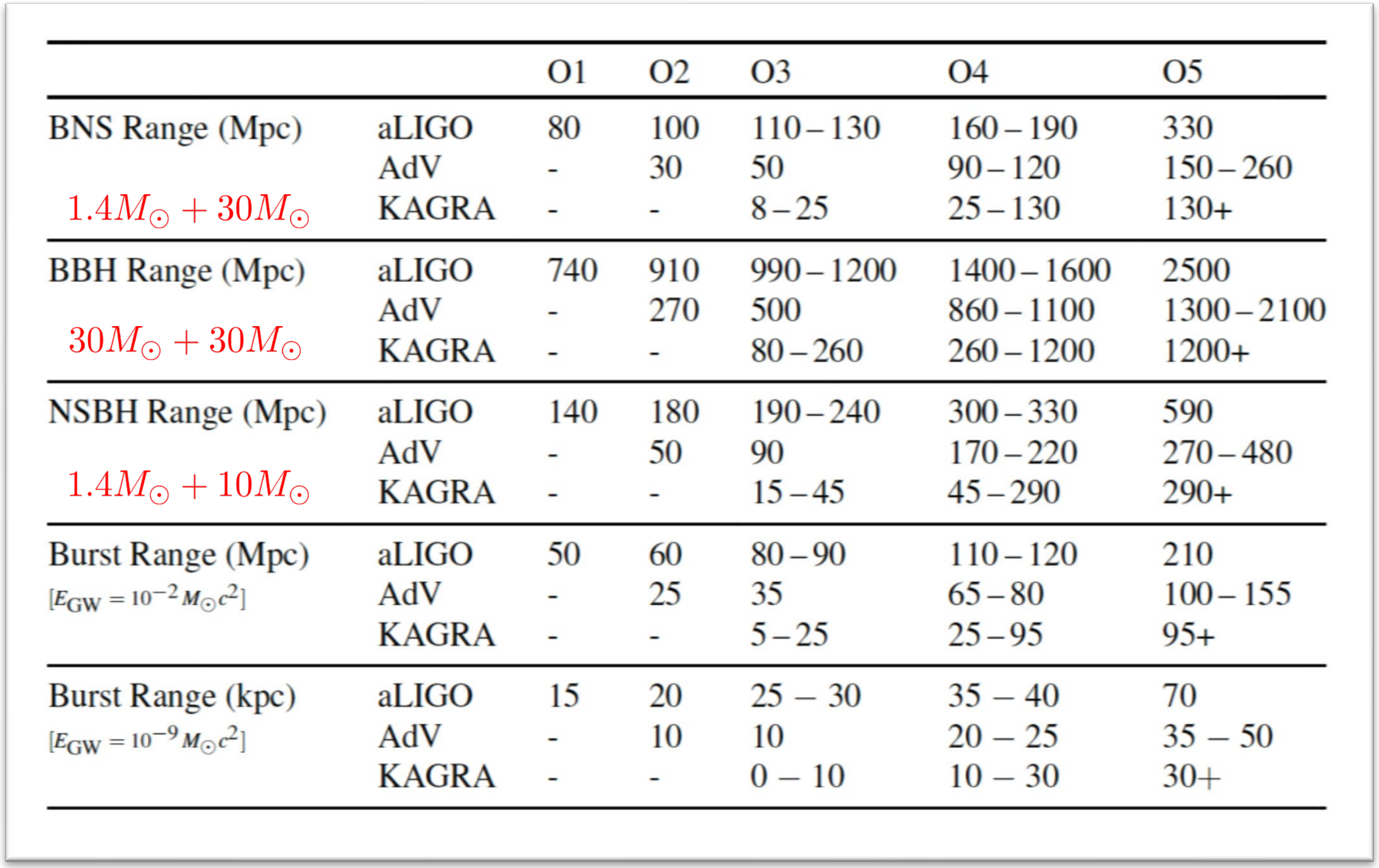
The 2σ exclusion limit and 5σ discovery potential obtained from LIGO and LISA after 2 yr of coincident running for B dark photon dark matter. Coupling strength is normalized to EM coupling strength, i.e., $\epsilon = \alpha/\alpha_{EM}$, which is not constrained theoretically

From: Phys. Rev. Lett. **121**, 061102

Dark photon searches: see https://arxiv.org/abs/2105.13085 and references therein

O4: what we expect





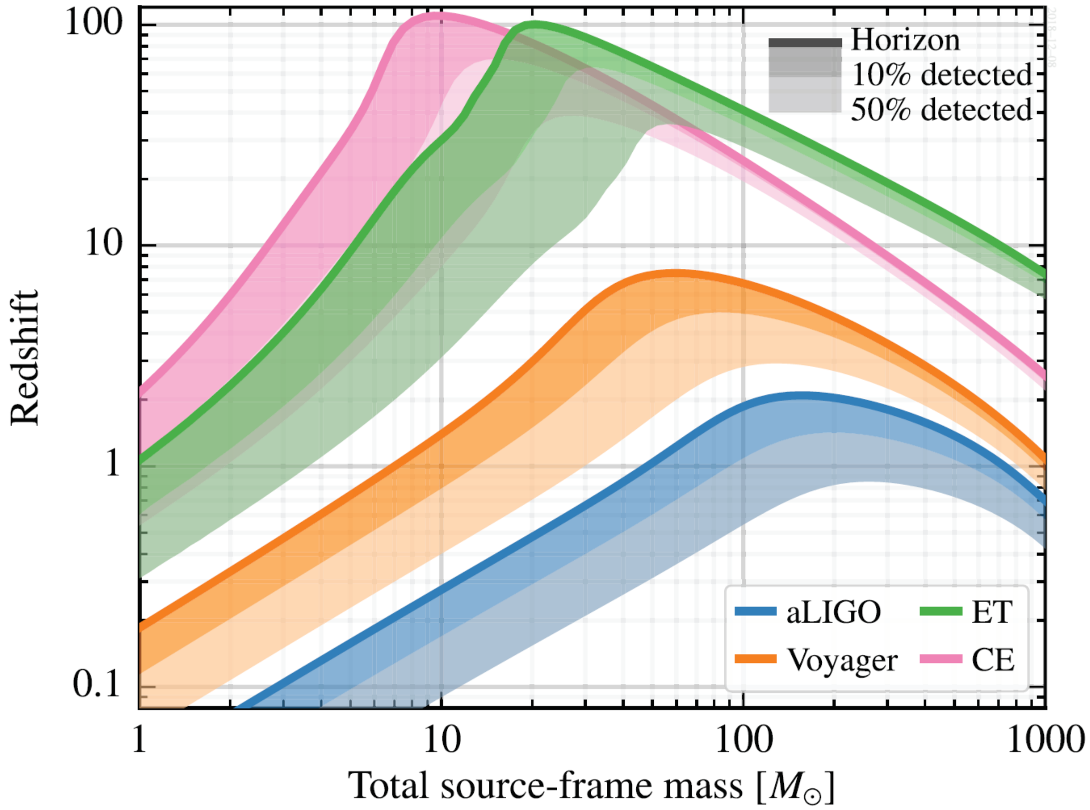
		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
$1.4M_\odot + 30M_\odot$	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
$30M_\odot + 30M_\odot$	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
$1.4M_\odot + 10M_\odot$	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc)	aLIGO	50	60	80 – 90	110 – 120	210
$[E_{\mathrm{GW}} = 10^{-2} M_\odot c^2]$	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc)	aLIGO	15	20	25 – 30	35 – 40	70
$[E_{\mathrm{GW}} = 10^{-9} M_\odot c^2]$	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

SNR = 8 on each detector

Living Rev Relativ **23,** 3 (2020). https://doi.org/10.1007/s41114-020-00026-9

Summary

- LIGO-Virgo and future GW detectors opening new windows for study of extreme astrophysical systems
- O3 provides new constraints on BBH population models, deviations from general relativity, masses of BHs, formation channels of massive BHs, and more
- Starting to explore
  - Neutron star astrophysics (structure? EOS? Vortex dynamics?)
  - Merger physics
  - Cosmology
  - Lensing
  - Multi-messenger astronomy (GRB, kilonova)
  - Connections with fundamental theories (dark matter, dark energy, graviton mass, Lorentz invariance bounds, speed of light, speed of GW, test of Equivalence principle)
  - Beyond GR (polarization of gravitational waves, testing GR in dynamic strong field regime)
  - Structure of BH (no hair theorem, exotic objects, QNM, echos, parity violation, axions)



A lot of work to do, and (hopefully) a lot of new scientific discoveries ahead.

Thank you for your attention….